ELECTRIC ARC PHENOMENA

BY

EWALD RASCH

TRANSLATED FROM THE GERMAN

BY

K. TORNBERG

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INTRODUCTION.

A REMARKABLE revolution is taking place in the fundamental conceptions of Physics. The Electronic Theory is furnishing wholly unexpected answers to the inquirer into the cause of light. This fact (in conjunction with other modern changes, such as improvements in incandescent lighting, etc.) imposes on the arc-lamp engineer the task of making improvements in the very principles of light production — a task which during the last decade has found, in the development of flame arc lamps, a provisional rather than a very desirable solution.

One cannot be taught how to find — only how to seek. Whether we succeed or not depends largely on whether our aim has been in a negative or a positive direction with respect to the object.

It is not within the scope of the present monograph to give an exhaustive review of the extensive literature which has accumulated on the subject of the electric arc and in which one is likely, quite often, to meet with contradictory statements.

The author considers, rather, that it is of paramount importance to separate the essential from the nonessential and to assist the student as well as the practicing engineer in those mental operations and elements of knowledge which involve fundamental principles and the mastering of which is indispensable for an understand-

ing of the present state of the art as well as for the stimulation of independent practical work of a progressive kind.

On account of the revolutionary trend in physical speculations on the fundamental cause of light, a few general remarks may appropriately be advanced here. This seems all the more necessary since engineering schools do not specialize sufficiently on this subject. Thus, such scientific facts as are known have not been put in a form to make them technically useful, by facilitating practical developments.

A satisfactory solution of the problem of economical light production by electrical discharges through gases presupposes a thorough understanding of numerous phenomena derived from quite remote fields of knowledge. For instance, besides purely electrical relations, there are to be considered important practical questions pertaining to arc stream conditions, the characteristics of different forms of discharge and the requirements for equilibrium.

The nature of electric conduction through incandescent gases and the relation of conductivity and light intensity to temperature point to facts and theories which are part of modern physical chemistry, while the selective radiation of incandescent gases is a branch of spectrum analysis. The electrode phenomena depend on properties of materials, on high-temperature chemistry and on the laws of black body radiation.

The peculiar phenomena of cathode and anode rays imperatively direct the attention to Newton-Weber's corpuscular theory of light — now almost forgotten — and to the electrodynamic theory of matter. The latter has been resurrected in the modern electronic theory, which is destined to govern with the irresistible force of inflexible truth even purely technical progress.

Furthermore, a new consideration, which has little in common with the usual technical problems of production and distribution of energy, enters here: When we speak of light we refer to phenomena which take place on the retina of the eye, thereby exciting in the brain certain psychic sensations which fall under the domain of æsthetics. In this connection are encountered problems concerning the distribution of sensitivity on the retina, color sensibility and synthetic color sensations — all questions which possess decidedly practical importance for the efficient generation of light by means of luminescent gases.

Finally, the thinking student will surely want to know something about the real nature of that which he is to produce and the service of which he is to enter. And if to-day Maxwell's theory is inadequate to give an answer as to the real nature of light and, therefore, cannot be taught with the same dogmatic unassailability which has been attributed to it in the last decade, the student has a right to know the explanations furnished by the electronic theory, which occupy the present-day scientists and which, as far as human intelligence can predict, contain the germs of future progress in electric-light engineering.

The technology of light thus covers a large field of knowledge to which numerous branches of science contribute and which would well merit the careful attention, also, of the political economist.

It must not be overlooked that a great, if not, indeed, the greatest, part of all electrical engineering work, even though by circuitous routes, aims at the economical production of light. But neither technical schools nor practical experience point out a sure way.

Unfortunately, the arc-lamp industry is subdivided, one

manufacturer building the *lamps* and another making *carbons*, while — to quote the words of a witty lawyer — " the *light* is made by the janitor " (who trims the lamps and switches them on). There is a great deal of truth in this last statement.

The engineering student is not more fortunate. All important progress and research work in regard to electric light production is done at the universities. This is not so by accident, since at such institutions the various branches of science are in closer touch than at technical schools. The latter, however, may have smoothed the way, by their intelligent thoroughness, for many a special branch of industry of less economical importance.

At any rate, schools of technology offer to the student neither a special course in light engineering nor even opportunity for suitable laboratory work which might take the place of such a course

It can easily be seen that this state of affairs can hardly be changed at the present time, and although during the last ten years the author has on several occasions spoken in favor of the creation of Chairs and Laboratories for electric-light engineering,* he would be at a loss to-day for a definite answer to this important question. Indeed, he would almost be inclined to doubt the wisdom of his former recommendations, for if we are to create new engineers we ought to know in advance where to find places for them.

Be that as it may, the fact is that in recent years there has taken place a progressive amalgamation of different branches of work and manufacture, formerly separate and self-contained. This has saved a considerable amount of intellectual effort by the general exchange of data; but,

* Vide "Über die Grundbedingungen einer ökonomischen Lichterzeugung," Bayerische Industrie und Gewerbeblatte, 1900, p. 38.

on the other hand, as a consequence, the demand on the individual has become much more severe.

As matters now stand, it is hard for a student to be sure of just what he must know, and still more difficult, for reasons already stated, to acquire thorough knowledge of the various branches of physical chemistry, of the theory of radiation, the electronic theory, physiology of the sensory organs, spectrum analysis, and to apply, independently, these studies to the particular problems which he has to solve. Very often he experiences more hindrance than help from the self-contained and academically perfect style in which the subject matter has been presented to him by the lecturer.

Theoretical Physics teaches the student the purely geometrical conceptions of the undulatory propagation of light, but tells him nothing as to how he is to generate this light economically.

Maxwell's electromagnetic theory of light, the ingenuity and elegance of his differential equations, the applications of these to Hertzian radiotelegraphy and the reverence for the logical perfection of the system presented, lead the student — with appropriate horror for forces acting across space and for the atomic conception of electrical units — to devote himself to speculations, or even to actual experimenting on the direct generation of light (Tesla's "Light of the Future"). Woe be to him if his faith has been great, for his failures will discourage him into a sceptical frame of mind toward all theoretical knowledge. In many cases the effect will be to retard industrial progress. Judging from our present knowledge it is safe to say that even the most obstinate efforts in that direction are, from the very start, doomed to failure.

It can be fearlessly asserted in these days — without

detracting from the reverence due the great genius of a Maxwell, a Helmholtz, a Hertz — that "Maxwell's electromagnetic theory of light" is not a theory of light at all.*

Maxwell's curl equations may be true, indeed, in regard to the phenomena of propagation of electromagnetic waves of great length; but they are inapplicable — and apparently fundamentally so — in case of shorter wave lengths and higher frequencies, i.e., in case of phenomena pertaining to light proper. They give not the least hint as to the ultimate physical cause of light, which is of such importance for the technical problems of light production.

The most profound treatises, such as, for instance, the one by M. Planck (1906), on "Theorie der Wärmestrahlung," are in accord with Maxwell's views, but arrive, by way of thermodynamic and kinetic reasoning, at the existence of an atomic unit quantity of electricity, while Maxwell's theory itself owes its consistency to the fundamental exclusion of any conceptions of just such electrical unit particles and forces acting across space.

The most determined attempts to use Maxwell's theory in connection with the mechanics of electrons have continually proved futile because, in the last analysis, they are as fruitless as attempts to breed with hybrids. They lead to Jeans-Lorentz' equation of radiation (1908), which contradicts authenticated experimental facts as to the distribution of energy in the spectrum, and they again relegate Maxwell's views to the field of very great wave lengths.

* Note added by the author during revision of manuscript:
At the eighty-first meeting (Salzburg, Sept. 21–25, 1909) of German Scientists and Physicians, it was unanimously agreed by the highest authorities on theoretical physics (Einstein, Planck, Born-Minowski, A. Sommerfeld and others) that "Maxwell's theory of the universe and his ether hypothesis must plainly be considered as obsolete."

Furthermore, the observed phenomena of the electronic theory correspond, in all essential points, to the predictions of Newton in his reports to the Royal Society (1671–1704) and to the views advanced and developed, more than half a century ago, by Wilhelm Weber (inventor of the telegraph) in his classical work, "Abhandlungen zur atomistischen Theorie der Elektrodynamik" (1846). It is usually claimed — with a reasoning hard to follow — that Hertzian waves could not have been discovered without the aid of Maxwell's electromagnetic theory of light.

Weber's theory of an atomic-electric unit quantity and his corpuscular theory of light have, furthermore, been misconstrued to deny the undulatory character of propagation phenomena, or even have been made responsible for the notion — which a mere tyro will recognize as absurd — that light consists of minute particles, "light corpuscles," which fly into our eyes like gnats.

It seems to the author that it is a matter of national pride to point out and correct some of these historical inaccuracies.

This is not the place to inquire into the source and purpose of the intrigues which have succeeded in perverting the simple, classical truth which characterizes all of Weber's works — intrigues which have caused them to be neglected for more than half a century. A few of Weber's own words, uttered in 1846, will suffice.

"If, for example, light undulations have any effect on the electrical fluids it is certainly to be expected that these effects will in time have the same periodicity as the light undulations themselves, thus resulting in electrical oscillations which, however, we have not been able to record with our present instruments. . . ."

"But Nature knows of slower vibrations, also, for example the acoustic; and the question naturally arises, whether there do not exist electrical oscillations which are due to such vibrations." . . . "I will give here at least one example of electrical oscillations produced by sound waves and actually demonstrate how such oscillations can be detected and studied with the aid of a dynamometer." . . . "That electrical oscillations such as will be practically demonstrated here actually took place under the conditions existing at the time of our observations, may be assumed at the outset. It is, therefore, necessary only to try out the method devised for the detection of such oscillations."

Weber then proceeds to give a demonstration with his dynamometer in a test arrangement which, by the way, embodies the principle of the telephone; after which he continues: "Now, after this method has been proven reliable, it can be used as a basis for further work. And it is certain that this method will lead to the detection of electrical oscillations under conditions where their existence has never before been suspected." (Papers read at the time of the foundation of the Royal Saxonian Society for the Advancement of Science. § 16, 1846.)

This prophecy was fulfilled, as is well known, by H. Hertz fifty years later.

It is difficult to imagine what our conception of the mechanism of the Universe would have been to-day if the trend of thought of the generation following Newton and Weber had progressed along the lines pointed out by these philosophers and now finally accepted by modern thinkers; and even though Sir William Thomson (Lord Kelvin), Tait and von Helmholtz, as late as the year 1874, thought they could dispose of Newton-Weber's corpuscular theory of light by the ironical, rather than seriously meant, de-

mand to be shown a "light corpuscle" and be allowed to examine the same, it is a fact that modern Physics has made this very thing possible.

The so-called "light corpuscles" — the electrons — which, for example, are shot out in immense numbers from incandescent oxide electrodes, have been investigated and their mass, charge and paths have been determined by experiments of wonderful and beautiful simplicity, thus proving the existence of electro-atomic emission centers in the sense of Newton-Weber's theory of light.

While on one side of the Channel, as late as the year 1874, there was renewed the perpetual ban upon Newton-Weber's corpuscular theory, with the great bitterness and perseverance which often characterize those who are in the wrong, and unconditional, dogmatical surrender to Maxwell's theory of light (or, rather, to an unwarranted extrapolation thereof) was demanded, — on the other side of the Channel, and in the same year, Crookes and Sheffield demonstrated in a brilliant manner, by means of the cathode rays discovered by the German scientists Plücker and Hittorf, the phenomena of "radiant matter": the emission centers of Newton-Weber which "constitute the borderland where energy and matter seem to merge." . . . "I believe that the greatest scientific problems will find their solution in this borderland, and even beyond it; it seems to me that here we have reached the ultimate realities." (Crookes, 1874.)

Maxwell himself is unprejudiced enough to interpret these phenomena, as does Crookes himself, in favor of the corpuscular theory.

While on the one hand it is announced that Maxwell's theory has once and for all banished from the sphere of cosmogonic conceptions the existence of forces acting across space, on the other hand Maxwell himself, with ingenuous

complacency, makes use of such forces in his kinetic theory of gases, according to which elemental units of mass (gas molecules) repel each other. On this basis he formulates his ingenious law of the distribution of velocity, the fundamental principles of which law had been previously pointed out by Gauss.

The electro-atomic philosophy, barred from the science of Physics, has progressed meanwhile along the sidepath of physical chemistry, has been blessed with a wonderful and practical productivity through the theory of ions, and has attached to itself names, such as Arrhenius, van't Hoff, Ostwald and Nernst.

To-day, two hundred years after Newton and fully a generation after Weber and Zöllner, the truths proclaimed by them have again, after an unparalleled struggle against oblivion, come to the surface in Lorentz-Einstein's electronic theory and Minkowski's four-dimensional electrodynamics.

This strife could easily throw a dismal light on the great of our nation. Blind animosity has characterized this combat, surcharged with malice. Even Goethe has taken part therein, as is evident by the very way he mentions the name of Newton. And some irresistible impulse has made him devote several volumes ("Beiträge zur Farbentheorie") of the sharpest kind of controversy against Newton, without making it clear to himself, or to us, what he is driving at or what he really is contending against. In point of fact, it is neither questions of the stomach, nor yet of physical science, which here collide, but purely metaphysical matters and cosmic philosophies which unconsciously are being fought about; and this ought to afford some relief, ethically, to the combatants.

But this consideration certainly cannot brush aside the

fact that the development of our mental pictures of a civilized world and of a physico-technical universe has been hindered, with more dire results, from the point of view of political economy, than were ever caused by the most bitter religious strife.

Richard Bentley, editor of Newton's works, in the year 1692 gave eight lectures for the purpose of establishing a foundation in honor of Robert Boyle (born A.D. 1626), discoverer of the law of gases. In these lectures Bentley " demonstrated the folly and absurdity of atheism," and by this, though inspired by honest intentions, he committed a fatal blunder. He used Newton's theory of gravitation and the existence of forces acting across space as a proof of the existence of God, and in the last of his lectures for this purpose took advantage of certain apparently concurring statements of Newton, whose religious zeal is well known. These utterances of Bentley and letters from Newton have defied to the utmost contradiction by the mechanical philosophy of the universe. One can follow this controversy step by step into modern times, with irresistible irony dragging into the fight, among others, Helmholtz-Maxwell against Newton-Weber-Zöllner, and creating the impression that above all one must beware of forces acting across space.

Von Helmholtz has made a fine play on words in referring to this baneful, though to a great extent unconscious, battle against windmills: " Metaphysical matters have as little connection with physical events as ' Gustave ' with ' Gasthof.' "

It has appeared to the author not useless to call attention to the foregoing facts, which, with exceptional force, should caution us to discreet tolerance and independent thought on scientific subjects, even in the face

of apodictic statements which, apparently, make independent speculation unnecessary.

If, in the following pages, the author refers a few times to his own work, he does so without conceit and only to counteract the common practice of making use of his results without giving due credit.

EWALD RASCH.

BERLIN-ZEHLENDORF,
January, 1910.

ELECTRIC-ARC PHENOMENA.

CHAPTER I.

GENERAL OUTLINE OF ELECTRIC-ARC PHENOMENA.

§ 1. History of Development.

THE electric arc furnishes a physical means for the transformation of electrical energy into light and its properties as a source of light will be principally considered here.

While most other branches of engineering are concerned merely with the generation, distribution and transformation of mechanical energy, the production of light constitutes an entirely different — a physiological — problem. In other words, it involves the generation of ether oscillations of definite frequencies, namely such — and preferably only such — as are capable of stimulating the retina of the eye, with the ultimate effect of exciting in the brain the psychic sensations which we call light. Among other things we will have to consider to what extent the electric arc is suitable for this purpose and what physical phenomena accompany and affect the operation and efficiency of this method of light production.

The discovery of the electric arc occurred within the same era in which, through Volta's discovery of the galvanic pile (1800), a low-resistance source of electricity became available. This offered a means, for the first

time, to obtain relatively large amounts of electrical energy. But it was not until seventy years later that the electric arc could become of practical importance as a source of light when, thanks to the invention of the dynamo by Werner von Siemens, Hefner Alteneck and others, a convenient and economical source was provided, which substituted electrodynamic action for the electrochemical action of galvanic primary cells. Thus it became possible to transform mechanical energy into electrical energy in any desired amount.

It seems remarkable that the electric arc was known only in the very form which it retained up to the beginning of the present century — although investigated for a long time by physicists — before the art of electric generation and distribution had advanced so far as to admit of its practical application to electric lighting.

Electric spark discharges between metallic electrodes, such as were obtained by Volta by means of the galvanic pile named after him, differ in principle from the electric arc as we know it, by the enormous resistance of the gaseous path — the spark gap — necessitating high potentials at the electrodes. Discharges involving large currents which, in accordance with our present views, are referred to as electric arcs, could not be known until a source of electricity of low internal resistance had been invented and a suitable electrode material — carbon — had been adopted.

When such large current discharges were produced the conductivity of the gas column between the electrodes was enormously improved. In the case of spark discharges between metallic terminals, the path for the current consists mainly of the poorly conductive atmospheric gases. Carbon electrodes, on the other hand, give off incandescent vapors and solid particles which

offer a path of good conductivity, in which relatively large amounts of energy can be transformed.

Probably Davy was the first to observe the altered characteristics of spark discharges, as they were known then, by this change in the operating conditions. He produced spark discharges between two pointed carbon rods and described the appearance of the discharge as follows:

"I found that the electrodes of this material, when connected to the terminals of a voltaic pile, possessed the same properties as metallic bodies in respect to the production of sparks."*

In a lecture before the Royal Institution, he further called attention to the fact that spark discharges between carbon terminals were more powerful than between the metal electrodes usually employed and "of a vivid whiteness." But, so far, he still had reference to discontinuous discharges of high potential and low current, as distinguished from comparatively low voltage, continuous discharges of greater current densities.

That same phenomenon — which then was in the air, so to speak — was exhaustively studied at nearly the same time by a number of noted scientists; in Germany, by Ritter of Jena, Tromsdorff of Erfurt, Gilbert and Pfaff; in France, by Foucroy, Vauquelin and Thénard.

The history of the electric arc can be touched upon here only to the extent that is necessary for an understanding of the physico-technical development of this problem.† It is, however, proven by the manuscript notes of Davy that a stable flame discharge of considerable current density between carbon electrodes was first produced and

* Priestley's "History of Electricity," p. 598.

† For a more complete history see Hertha Ayrton's "The Electric Arc," London (1902).

studied by him sometime in the years 1808 and 1809. But not until the year 1812 does he give a complete and clear description of the arc.*

Whether W. Petroff — as claimed by E. Smirnoff — in the year 1802 had already discovered and known the electric arc, may be left undecided.

In any case, it is the indisputable merit of Davy, by virtue of his intuitive penetration, to have found out that discontinuous spark discharges can be changed to stable flame discharges of great current density by the employment of carbon electrodes, a series resistance and the selection of a suitable voltage.

The electric arc, essentially as known by Davy and as it has found application in arc lighting up to the present time, will be treated, in its physico-technical aspects, in the following.

§ 2. The Formation of Electric Arcs by Contact Starting.

If the tips e_1 and e_2 of two suitably pointed carbon rods A, K (Fig. 1), connected to a source of electricity,

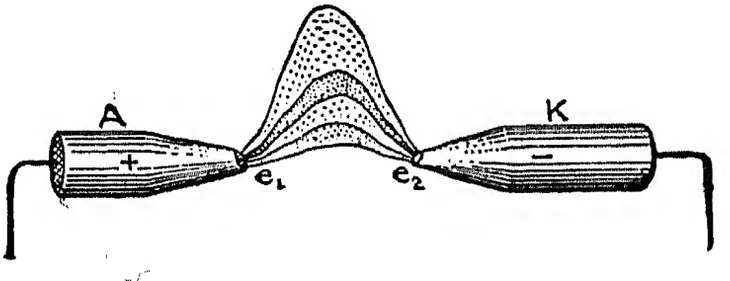


FIG. 1.

be brought into contact with each other, the electric current, if the voltage is sufficiently high, will pass from the electrode A to the electrode K, since the conductivity of carbon is relatively good. A certain amount of contact resistance will occur at the contact surfaces. The joulean heat developed hereby, however, is confined to

* "Elements of Chemical Philosophy" (1812), Vol. I, p. 152.

the point of contact — a fact of considerable importance in the formation of an arc — the more so as the actual contact never occurs between any considerable portions of the surfaces e_1 and e_2, but only between protruding points thereof. On account of the great current density at these points the surfaces e_1 and e_2 become white hot and begin to volatilize.

If the carbons now be drawn apart (thus discontinuing the contact) a relatively good conductive gaseous path for the current will be formed, partly by the white-hot vapors (carbon monoxide, carbon dioxide and solid carbon particles), partly, also, by the highly heated air stratum between the basic surfaces (e_1, e_2). This gas column permits a continuous transmission of the current between e_1 and e_2 and is, itself, maintained at white heat by the passage of the current.

In the strict sense of electrochemistry, not the carbons themselves (A, K, Fig. 1) — since their length is arbitrary — but only the basic surfaces e_1 and e_2 are the "electrodes," from which the current is introduced into the electrically conductive medium of the arc flame.

Since the above method for starting the arc — by bringing the electrodes into contact with consequent heating of the base surfaces e_1 and e_2 — is of importance for the technology and classification of the various forms of arcs to be described later, this particular method will be referred to, briefly, in the following as contact-starting or self-starting.

When the carbon rods (A, K) are held in a horizontal position or, in other words, when the electrode bases are vertical, the flamelike current bridge assumes an arched shape due to the ascending heated air, as indicated in Fig. 1. This configuration caused Davy to designate the phenomenon an "electric arc." The term, although now

generally adopted, loses its appropriateness when the carbons are vertical. The phenomenon observed by Davy was plainly the prototype of the electric flame or arc.

§ 3. Electrodes of the First and Second Class. Mixed-class Electrodes. Auxiliary Starting.

The heating effect of the arc is not confined to the arc hearth only, but through conduction the adjacent portions of the carbons naturally become hot also. Granqvist has shown * that of the total energy 79 per cent is lost — 42 per cent from the anode and 37 per cent from the cathode — due to this heat conduction. In this connection attention may be called to the fact, established by Arons, that it is impossible to maintain an alternating-current arc between metallic electrodes on account of their great thermal conductivity which is a characteristic that usually is associated with, if not actually proportional to, good electric conductivity. Through heat conduction so much energy is lost from the arc bases that the arc can only with difficulty be started anew at each reversal of the current, since the heated gas column cools off rapidly and thus loses its electrical conductivity.

Of course, it must be possible to maintain an arc by means of alternating current between metal electrodes if one introduces a conductive flame as, for example, the flame from a Bunsen burner in which alkaline salts are being volatilized. Owing to their low melting points, however, metal electrodes will not carry any considerable currents without becoming fused. Despite this fact, arc flame discharges can be produced between metallic electrodes even when the melting point is comparatively low, as exemplified by Birkelland-Eyde's process for the oxidation of atmospheric nitrogen. In this process electrodes

* Phys. Zeitschr., 4, p. 537 (1903).

of copper (melting point 1085° C.) are used. But this is possible only by the employment of high voltages, i.e., by keeping the current density low at the ends of the electrodes and protecting the electrodes from the arc flame by an intermittent magnetic blow, or preventing them from melting by some other means, such as artificial cooling.

The only metallic arcs of practical interest for lighting, therefore, are those produced between metals already liquid, as in Arons-Cooper Hewitt's mercury vapor lamp, in which the oxidation of the electrodes is prevented by the exclusion of the atmospheric oxygen.

Common to both kinds of electrodes mentioned (carbon and metals) is their property of burning in the air, forming solid or gaseous oxides; also their relatively high conductivity at ordinary temperatures. This latter property is a prerequisite for contact starting of arcs. Oxidizable electrodes which, like carbon and the metals, consist of conductors of the first class, that is, chemical elements not decomposable by electrolysis, we shall designate as *electrodes of the first class.*

The definition of the electric arc used even in modern times: *

1. That it must be possible to start the discharge "by contact and subsequent separation of the electrodes" (contact starting);
2. That the discharge phenomena must be stable;

contains, in its first part, a definitional overstatement. The contact action, *per se,* is neither absolutely necessary for the formation of an arc, nor is it always a sufficient criterion. It has been shown (E. Rasch, 1899)†

* Reports Deutsch. Phys. Ges., 7, 157 (1903); see also "The Electric Arc," by H. Ayrton, London, 1902, p. 20.

† Means for the production of electric arcs: German Patents Nos. 117214 and 137788, March 18, 1899. See also E.T.Z., 1901, p. 155.

that stable electrical discharges through gases and large-current electric arcs can be maintained — in vacuo as well as in the open air — even between nonoxidizable substances such as are generally classed among the best nonconductors (oxides, fluorides, silicides, borides and similar metal compounds), if through auxiliary heating of the electrode tips the initial starting of the arc is brought about or kept up.

Yes, it has been found and is proved by the observations of E. Rasch (1899),* E. Bose (1901),† Wehnelt (1903),‡ J. Stark (1904),§ F. L. Tufts ‖ and others, that metallic oxides and other conductors of the second class, after being heated to conductivity, have, in far greater degree than conductors of the first class, the surprising property of sending out electrically charged corpuscles, that is, of making gases conductive. They possess an incomparably greater power of ionization than metals and even than carbon; in short, they are by far the better arc producers.¶ To distinguish the large and characteristic group of electrodes consisting of chemical compounds (metallic oxides, fluorides, borides, silicides, etc.) from the oxidizable electrodes, the former will be designated in the following as *electrodes of the second class*.

Electrodes which consist of a combination of conducting substances with conductors of the second class form an intermediate link between the other two sharply differentiated groups and will be referred to in the following as *electrodes of mixed class*. Such electrodes are pecul-

* E.T.Z., **22**, 155 (1901); Phys. Zeitschr., **5**, 375 (1904).

† Ann. d. Phys., **9**, 164 (1902).

‡ Erl. Ber., p. 150 (1903).

§ Phys. Zeitschr., **5**, 81 (1904).

‖ Ibid., **5**, 76 (1904).

¶ E. Rasch, "Gasentladungen an elektrolytischen Glühkörpern," Ann. d. Phys., **11**, 202 (1903).

iar to the various kinds of so-called flame carbon arc lamps. According to the percentage of nonoxidizable material contained, the arc and the mechanism of light generation will resemble, more or less, those of electrodes of the first or second class.

Characteristic of conductors of the second class is their enormous specific resistance at ordinary temperatures, as well as their high dielectric constants. Whereas, in metals, the resistance r increases with the temperature, the reverse is the case in conductors of the second class, the resistance decreasing very rapidly as the temperature is increased.

For the former class of conductors the temperature coefficient is positive, viz.:

$$\frac{dr}{r}\frac{1}{dT} = +\alpha,$$

and for pure metals is approximately the same as the coefficient of expansion for gases,

$$\alpha = \frac{1}{273}.$$

However, for conductors of the second class (metal compounds), the relation between conductivity $\kappa = \frac{1}{r}$ and temperature T is expressed by the differential equation *

$$-\frac{d\kappa}{\kappa} = \frac{dr}{r} = -\frac{C}{T^2}dT.$$

This indicates that the temperature coefficient $\frac{dr}{r}\frac{1}{dT}$ of electrical resistance (r) is negative, since the specific resistivity decreases proportionally with the exponential term

* "Fortschrittliche Prinzipien der Lichttechnik," by E. Rasch, Potsdam, 1903, p. 18.

$e^{\frac{c}{T}}$ — thus very rapidly — and tends, for infinite temperature T, asymptotically towards nearly zero value.

It is noteworthy as indicating the close connection between the mechanism of light production and the conduction of electricity that the increase in surface brightness, Φ, of incandescent solid bodies with temperature follows — as shown by the author's deductions given elsewhere * — the differential equation

$$\frac{d\Phi}{\Phi} = + \frac{K}{T^2} dT,$$

an equation which is of the same type for both processes. ($K = 25{,}000$.)

For zirconia-yttria arc electrodes the author has arrived at a value for the constant C at temperatures up to 1200° C., as approximately being of the order

$$\frac{K}{3} = \frac{25{,}000}{3}.$$

We shall return to this relationship later.

Since arc-lamp electrodes of the second class are practically nonconductive at ordinary temperatures, the arc bases cannot become heated, and a gaseous path be provided for the arc, merely by bringing the electrodes in contact with each other. To start an arc, it therefore is necessary to heat the electrode tips by auxiliary means until they become conductive. After this has been done it is easy to start the arc by contact, even in the open air. If a separate flame, such as an auxiliary arc between carbon or metal electrodes, be used for the initial heating, the conductive gases from this flame will cause an arc to form between the main electrodes, even without their

* Zeitschr. f. Elektrotechn. u. Maschinenbau, 1903, Nos. 4–12. Cf. Ann. d. Phys., 14, 193 (1904).

being brought in contact at all. The same is the case when such electrodes of the second class are enclosed in a vacuum and heated by a resistance coil.

According to F. L. Tufts "the discharge current obtained with an E.M.F. of 150 volts is about 600 times greater" for oxide electrodes than for platinum electrodes, other conditions being the same.

J. Stark (*l. c.*) has closely studied "the starting of arcs between oxide electrodes" and calls attention to the ease with which glow discharges are changed into arc discharges when conductors of the second class are used for arc terminals.

J. Stark has further drawn the important conclusion that preheating of the electrode tips is theoretically an absolutely necessary condition for the initial starting and continuance of an arc, not only between electrodes of the second class, but between any kind of electrodes (carbon, etc.).

A stable arc is possible and can be sustained only when the cathode surface e_2 (Fig. 1) has a sufficiently high temperature.

This finding of J. Stark possesses equally theoretical and practical importance and has enabled us, only recently, in connection with the views of the electronic theory, to obtain an insight into the often extremely obscure phenomena which accompany the electric arc and discharges through gases.

Broadly speaking, one must designate as an electric arc any continuous discharge occurring between electrodes of different potential and serving as a source of light, where at least one of the electrodes — the cathode — is kept at a high temperature either by the current passing or by auxiliary means.

Obviously, it is not necessary that these discharges

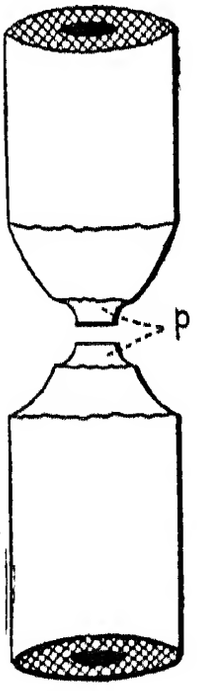
involve currents of great strength, as in the modern arc lamps. On the contrary, it is easily possible to conceive an arrangement whereby the phenomena taking place in connection with electrical discharges in a vacuum may be made to serve as efficient sources of light, if only the physiological peculiarities of the eye could be suitably taken advantage of.

CHAPTER II.

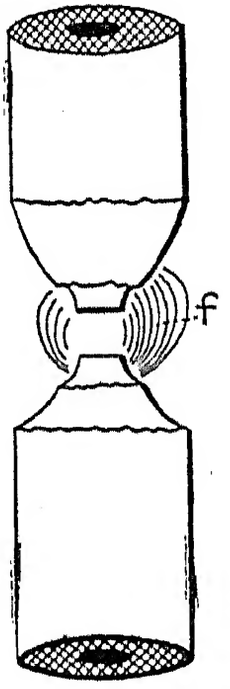
THE TYPICAL CARBON ARC. EXTERNAL PHENOMENA. ARC ADJUSTMENT.

§ 4. The Alternating-current Arc.

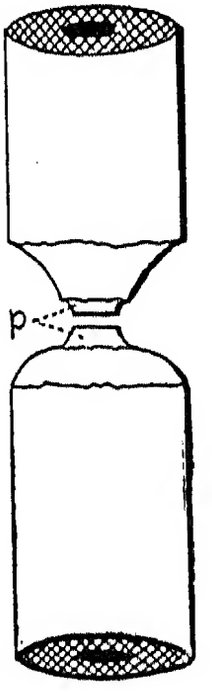
If an arc be started between two vertically placed commercial arc-lamp carbons, by means of contact or in other ways, it will be found that, after they have been burning a sufficient time, the shape of the ends of the carbons will be altered in a conspicuous manner. If the oxygen of the air has free access to the arc, both electrodes will generally become more or less pointed.



Arc Voltage Normal.
Fig. 2.



Arc Voltage too High.
Fig. 3.



Arc Voltage too Low.
Fig. 4.

In the case of alternating current and with carbons — usually cored — of the same diameter, both ends will be nearly symmetrical in shape (see Figs. 2 to 4). The high-

est temperature will be at the two opposite tips (p, p) which will become white hot and form the bases for the transfer of the current from one carbon to the other.

From these surfaces — the electrodes proper — by far the greater portion of the light is produced and given out. There is a not inconsiderable heating of the carbons immediately behind, through conduction from the points of greatest energy density. However, the temperature decreases rapidly from the electrode tips backwards. Thus, the larger portions of the cones forming the electrode ends will show only a dark red glow, while the cylindrical part behind will be relatively cold. On this portion the sublimed mineral impurities of the carbons will deposit as a white coating. Most of the time a bead of glasslike tiny drops will be formed around the broad part of the electrode cones. These drops consist of boric acid, silicates and similar impurities in the carbons, and are being vaporized as the carbons burn away and partly again condensed.

Usually, and preferably, both carbons are cored. They consume at the same rate, and therefore both carbons should be of the same size.

§ 5. The Continuous-current Open Arc.

While in the case of an alternating-current arc burning with free access of air both electrode ends at which the main transfer of current takes place will burn away symmetrically, a continuous-current arc will cause considerable dissimilarity in the shape of the active electrode tips.

In a continuous-current arc the negative electrode, the cathode, plays the more important part, even though — for other reasons — the positive electrode, the anode, usually placed above, possesses a higher temperature and gives out more light than the cathode.

It has been shown (§ 3) that an independent arc can form and exist only when the cathode is brought to and kept at a high temperature.

If the cathode be purposely cooled in any suitable manner, it is impossible, with low-potential difference, to start and sustain a stable arc. This explains the fact (§ 3) that an arc cannot be maintained between metallic electrodes with alternating current of moderate voltage. In the first place the arc goes out at each reversal of the current, and in the second place the great heat conductivity of the metals causes the constantly changing cathode to grow too cold at each reversal to give off negatively charged electrons.

But the conductivity of the gaseous path between the electrodes, as well as the possibility to start and sustain an arc, is dependent on the presence in this path of such electrons. This is not to be understood to mean that an arc between a cold cathode and a cold anode is an absolute impossibility. On the contrary, such an arc — although not as yet actually accomplished — is theoretically conceivable, namely if sufficiently ionized and conductive gases be introduced into the current path between anode and cathode, for example, by means of a separate flame.

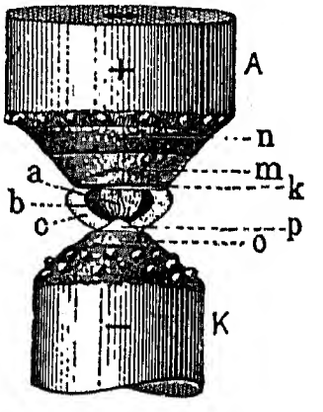


FIG. 5.

On the conical end of the anode *A* (see Fig. 5), the continuous-current arc causes a dish- or funnel-shaped hollow, the anode crater *k*, while the cathode becomes pointed to a wart *p*.

The greatest energy density and highest temperature occur at the crater *k* of the anode and the point of the cone *p* of the cathode. The two electrode portions mentioned become dazzlingly white hot and form the bases for the (current) streamers which constitute the

arc proper, — the current transmitting flame, *a*, *b*, *c* (see Fig. 5).

Three distinct zones can be easily distinguished in the arc flame, *a*, *b*, *c*. The innermost part thereof, *a*, forms a violet core (the cyanogen flame). This is bordered by a dark envelope, the so-called "black band" *b*, this in turn being surrounded by the "aureole" *c*, of a green or greenish yellow color.

Although the anode crater (*k*) is larger than the current-carrying wart of the cathode, the former nevertheless possesses a higher temperature, a greater specific density of energy and a greater total radiation than the latter. The anode crater radiates about 120 hefners per square millimeter of luminous surface. The electrical energy dissipated at the anode amounts to about 20 watts per square millimeter of the crater surface projection. Moreover, the anode crater acts, in a sense, as a reflector upon which the cathode radiates its heat. The temperature decreases rapidly towards the adjacent portion, *m*, *n*, *o* (see Fig. 5), of the electrode ends. The conical shape which the latter assume is due, probably, to the more or less slow oxidation to which the carbons are subjected by the unrestricted access of the atmospheric oxygen. The same is true of alternating-current arcs (see Figs. 3 to 5).

In alternating-current arcs cathode and anode change places at every reversal of polarity. As a result both electrodes behave alike with respect to shape, temperature and radiation.

The cathode and the anode of a continuous-current arc, on the contrary, show quite different effects in regard to drop of potential, light-giving properties and heat distribution. Corresponding to these differences there is a marked difference in the rate of consumption, i.e., a

more rapid one of the upper, usually cored, anode as compared with the cathode for which generally a solid carbon is used. To obtain the same linear consumption of both it is customary to make the positive electrode about 50 per cent larger in diameter than the lower, negative electrode.

§ 6. The Enclosed Arc.

The effect of oxidation of the electrodes is clearly apparent by comparison with the peculiar shape assumed by the carbons of an enclosed arc, in which by restricting the supply of oxygen to the arc the oxidation of the electrodes is considerably retarded.

The carbons — usually uncored — do not become at all pointed as in the case of continuous- and alternating-current open arcs.

The shallow cavity formed at the anode *A* (Fig. 6) only faintly resembles the crater of the continuous-current arc, and the cathode becomes a slightly convex surface corresponding in curvature to that of the anode. Between these two surfaces, equidistantly apart, the arc wanders around, seeking out the spots where momentarily the supply of oxygen is the greatest due to local air currents within the enclosed space.

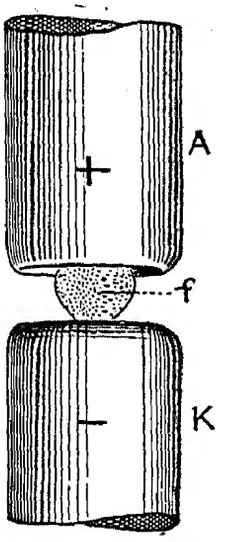


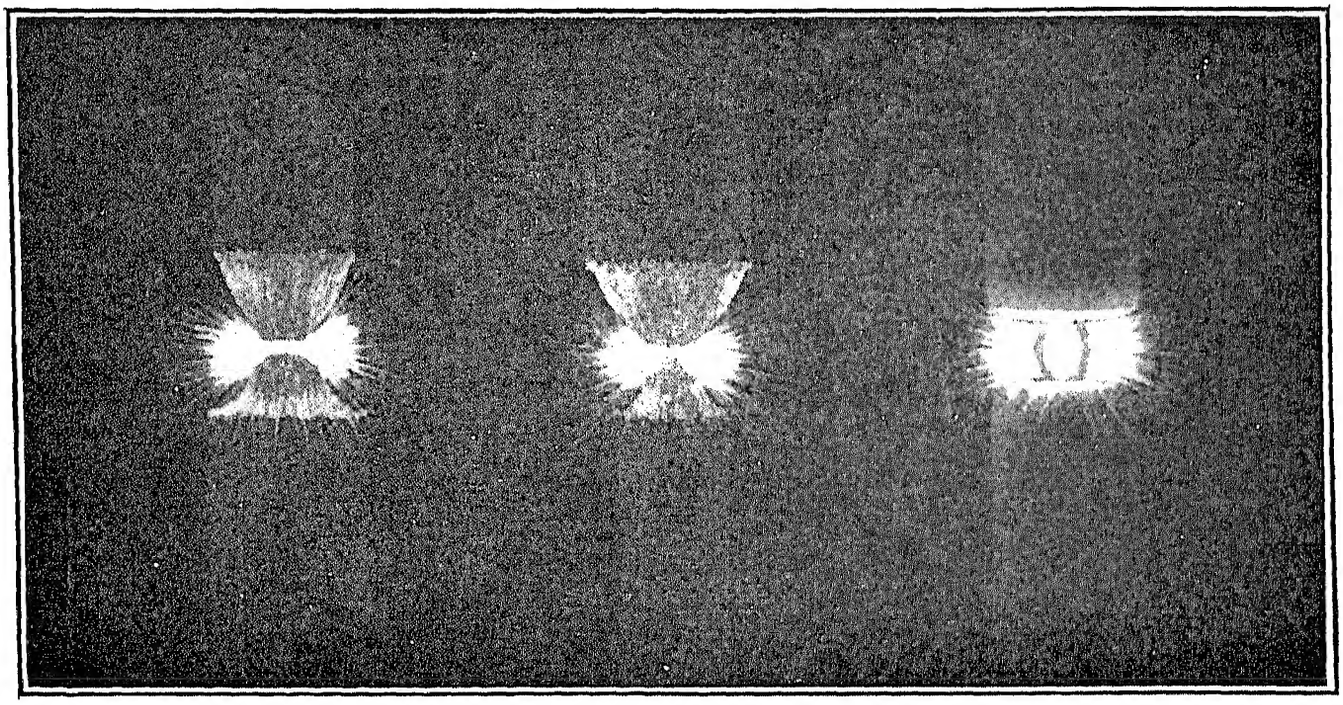
FIG. 6.

Another result of the limited oxidation of the enclosed arc is the fact that coring of the carbons is without any advantage to speak of, as the arc does not tend — as in the case of the "open" arcs — to stay on the electrode core which develops the conducting vapors.

The characteristic structure and color peculiar to continuous- and alternating-current open arcs is also wanting

in the enclosed arc. It consists mainly of the cyanogen flame, — the violet core *a* (Fig. 5) of the open arc, — but is without the black band *b* as well as the aureole *c*. This seems to justify the conclusion that the latter are depending for their formation on reactions with oxygen.

It is due to this violet cyanogen flame that the enclosed arc is so much more photochemically active than the open arc.



Alternating-current Open Arc. FIG. 7.

Direct-current Open Arc. FIG. 8.

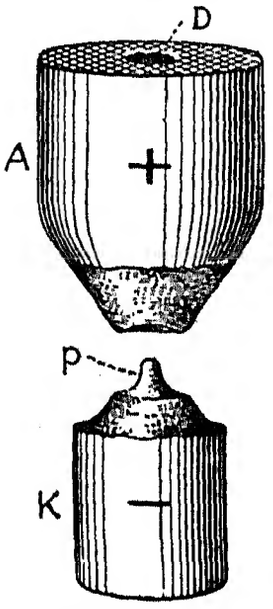
Enclosed Arc. FIG. 9.

Figs. 7, 8 and 9 show typical differences between the outward appearances of the three forms of arc.

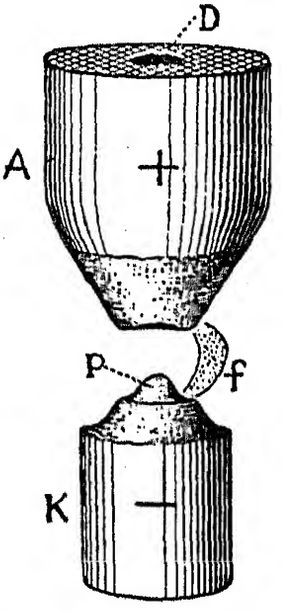
§ 7. Adjustment of the Arc.

1. As has been stated (§§ 4 to 6), after the arc has been burning a sufficient time, the electrode ends will assume quite definite typical shapes which are necessary concomitants for steady operation. This latter seems to depend more on proper shape of the electrode tips — and especially that of the cathode — than on the arc length.

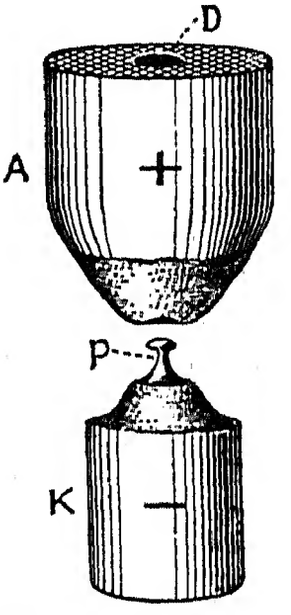
To make necessary adjustments the arc is observed through a colored glass, and voltage and current are adjusted by hand until the ends of the carbons have assumed permanent shapes determined, on one hand, by the electrical conditions and, on the other, by electrode dimensions, etc. Obviously, rules for doing this can only be indicated here. Practical observation will soon give sufficient guidance. It should be remembered, however, that this forming of the electrodes will take some time and that, thus, it is necessary to wait until their shapes have become stable.



Arc Voltage Normal.
FIG. 10.



Arc Voltage too High.
FIG. 11.



Arc Voltage too Low.
FIG. 12.

2. *Continuous-current Arc.* — The anode is cored and is placed above the cathode which is solid carbon.

a. The arc voltage is too low, the arc itself too short and the point *p* too long. (Fig. 12.)

The point *p* shows a tendency to form a mushroom-like protuberance which threatens to touch the anode *A*. The arc has a tendency to hiss. The light is altogether unsatisfactory.

The arc voltage is to be raised by lowering the series resistance.

The increase in voltage results in transforming the mushroom into a needle point. Even now, however, the voltage is too low.

b. The arc is normal. (Fig. 10.)

The tip *p* of the cathode has rounded itself like a finger tip, not too flat.

c. The arc is too long, the arc voltage too high. (Fig. 11.)

The cathode wart has disappeared and given place to a relatively flat finger tip. The arc burns unsteady. On

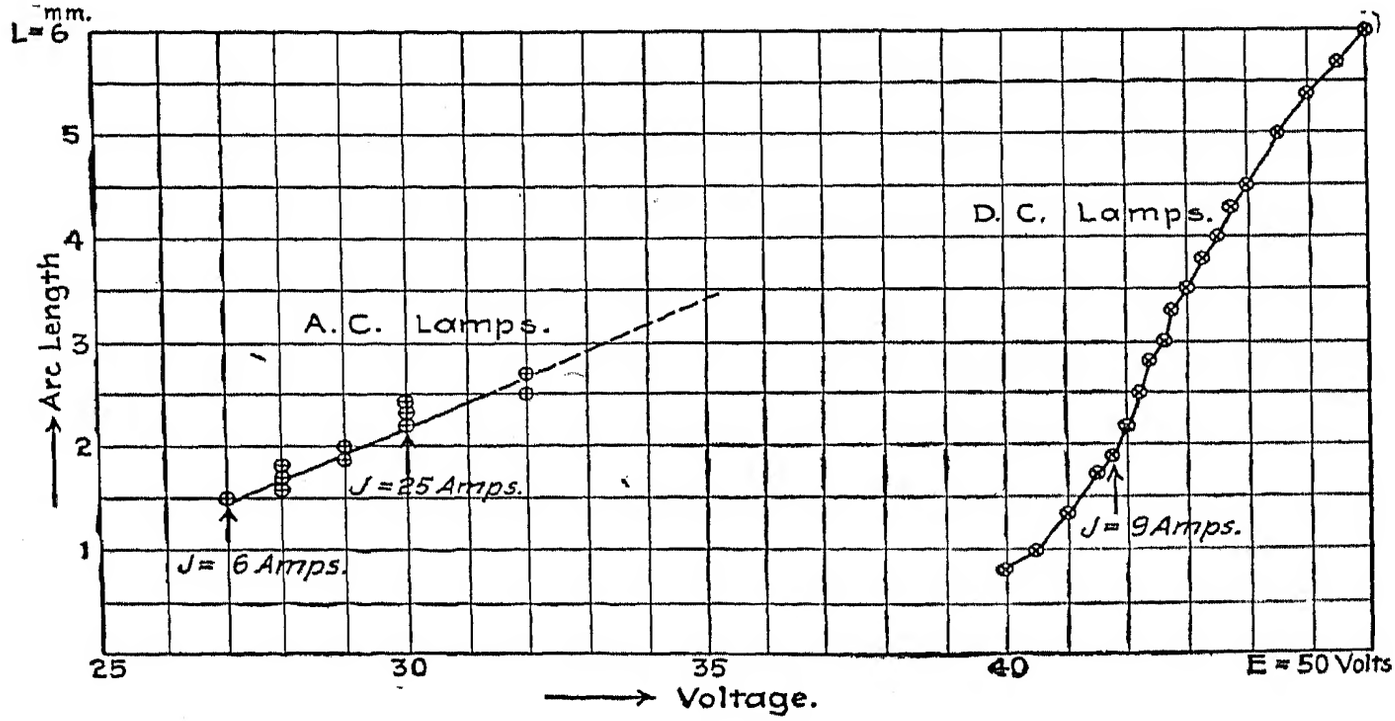


FIG. 13.

the edge of *p* a scythe-shaped violet flame occurs which is accompanied by flickering.

The voltage must be lowered.

3. *Alternating-current Arc.* — Usually both carbons are cored.

a. The arc is too short and the arc voltage too low. (Fig. 4.)

The electrodes threaten to come together. The arc whistles and the light is unsatisfactory.

The arc voltage is to be raised by cutting out some of the series resistance.

b. The arc is normal. (Fig. 2.)

The electrode tips *p*, *p* form horizontal parallel surfaces. No arc flame should be visible.

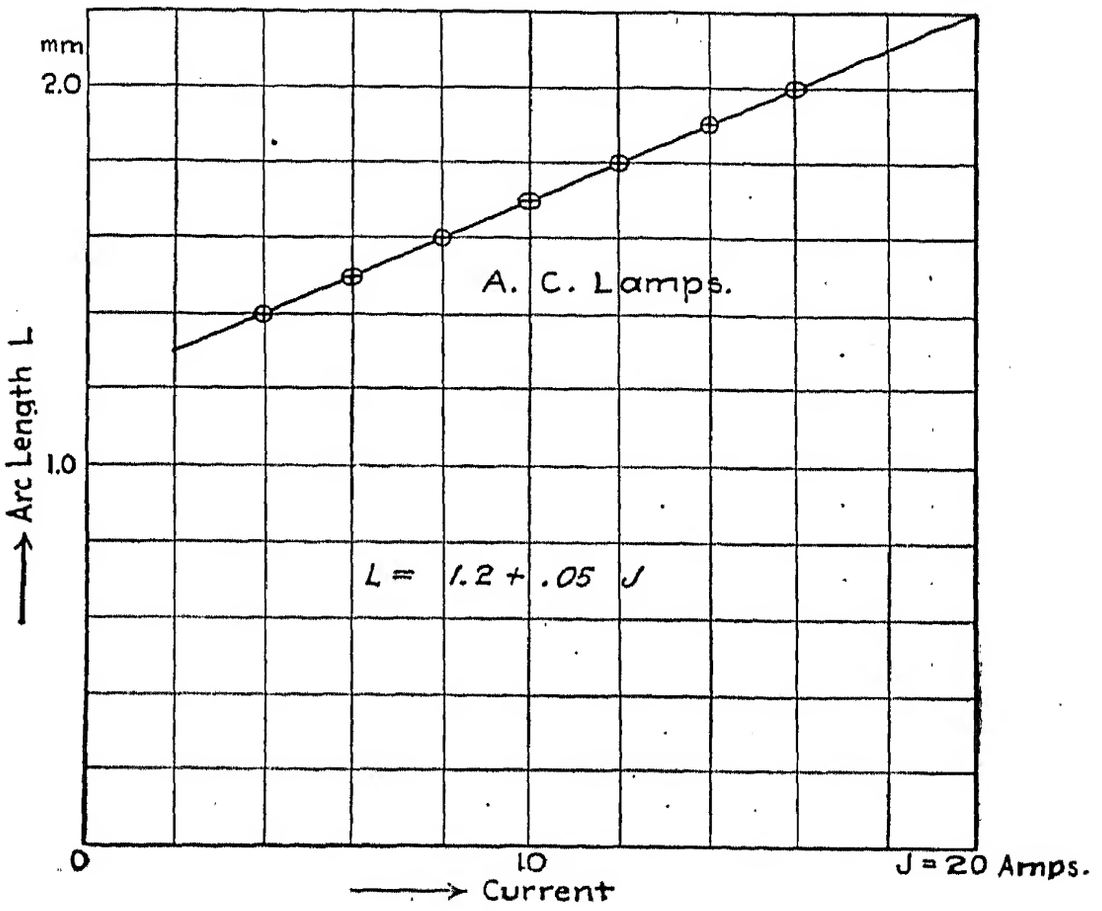


FIG. 14.

c. The arc voltage is too high, the arc too long. (Fig. 3.)

An unsteady violet flame *f* appears. Now and then tiny molten particles are sputtered from the crater.

The arc voltage must be lowered by increasing the series resistance.

It is advisable always to try to adjust the arc by means of the series resistance alone. Only when it is apparent that this will not suffice should one alter the arc length by means of the lamp mechanism.

4. As seen from the above it is not possible to give any general rules as to the most suitable arc length. The latter depends on the number of lamps in series, on the margin for adjustment in the available voltage as well as on the quality and the cross-section of the carbons. Direct observation of the burning is here the only practical guide.

The diagram, Fig. 13, will give an idea of the arc lengths commonly used with various arc voltages, in the case of ordinary carbons of the usual dimensions.

The diagram, Fig. 14, shows, for alternating-current lamps of the usual kinds, how the arc length in millimeters is derived for a given current J, in amperes, according to the formula,

$$L = 1.2 + 0.05\,J.$$

We shall return later to the general principles governing arc voltage and current and their relation to arc length and the conditions for steady operation.

CHAPTER III.

TYPICAL ELECTRODE MATERIALS AND THEIR PHYSICAL PROPERTIES.

§ 8. The Physical and Chemical Properties of Carbon.

1. CARBON, the substance which Davy used for arc electrodes, possesses a number of conspicuous physical peculiarities, which probably account for the fact that this material has been, up to very recently, adhered to almost exclusively for electric arc lamp purposes, and that one has come to regard the phenomena of the arc as to a certain extent connected with this kind of electrodes.

Although the carbon group in the periodic system of elements includes, as related to it, the metal tin, carbon lacks many of the properties characteristic for metals. As will be seen by referring to the table below, carbon is located farthest from tin in the carbon group.

TABLE 1. CARBON GROUP OF ELEMENTS.

Element.	Atomic weight.	Specific heat.	Atomic heat.
Carbon (diamond)	11.91	0.11	1.3
Silicon (crystallized)	28.2	0.17	4.8
Germanium	71.9	0.074	5.3
Tin	118.7	0.056	6.6

The otherwise abrupt gap between the two chemically related metalloids carbon and silicon, on the one side, and tin, with its pronounced metallic properties, on the other, is bridged by the rare element germanium.

One of the most remarkable of the peculiarities of car-

bon is that it can exist in three allotropic forms (diamond, graphite and amorphous carbon), the physical differences of which are more striking than in the case of any other element occurring in more than one form.

2. *Infusibility. Sublimation.* — Carbon does not melt at any attainable conditions of temperature and pressure.* This makes it peculiarly suitable as a material for electrodes. Even at the highest temperature obtainable in a Moissan's electric furnace there is not the least tendency to fuse. On the contrary, the surfaces of the electrodes appear perfectly "dry." The only effects discernible are a slight weakening (decrease in mechanical strength) and a considerable sublimation, i.e., the solid carbon passes directly — without previous melting — into the gaseous state.

Volatilization of carbon, however, takes place even at much lower temperatures, such as obtain in carbon filament incandescent lamps (about 1600–1700° C.). This sublimation is especially noticeable in case such lamps have been subjected to too high voltage, when it will show itself as a black deposit on the inside surface of the glass bulbs. It causes a reduction of the cross-section of the filament, with consequent increase in the lamp resistance, and is thus responsible for the limitation in useful life of incandescent lamps.

In connection with the typical carbon arc, however, these properties are exceedingly important and advantageous. The arc flame proper plays a comparatively subordinate part in this, since from the same only about 5 per cent of the total light is emitted. On the other hand, the white-hot solid tips of the anode and cathode are of paramount importance for the light production.

* This fact makes the prospects for the successful production of artificial diamonds rather small.

The typical carbon arc — in contradistinction to the so-called flaming or mineralized carbon arc — is, properly speaking, an incandescent source of light. However, while in the ordinary incandescent lamp it is necessary to limit the temperature and the current density of the filaments in order to obtain a long life, in the carbon arc the volatilization of the carbons need not be kept down. In fact, the energy density in the glowing, light-emitting surfaces (more especially the anode crater) is often purposely driven to the volatilization point of the carbon. This very circumstance, that it is expedient to sacrifice one of the economical considerations — the life of the electrodes — makes it possible to attain exceedingly high temperatures and energy densities at the luminous surfaces (up to 20 watts per square millimeter) which, as we shall see later, is the reason for the greater light efficiency of carbon arcs over that of incandescent lamps proper.

3. *The Arc as a Reducing Agent. Oxidation of the Carbons.* — Carbon possesses the extraordinary high heat of combustion of 8000 calories per gram, equivalent in electrical energy to 9.3 watt-hours per gram of carbon.

Correlated to this great proneness to oxidation is the ability of carbon to take away the oxygen from even the most difficultly reducible metallic oxides, to use it for its own combustion.

The carbon arc is thus a powerful reducing agent, by virtue of the white-hot electrode tips and the incandescent particles of carbon and carbon-monoxide gas in the arc flame.

Consequently, the carbon arc plays an important technical rôle in pyrochemical and metallurgical reduction processes, both directly as a reducing hearth and indirectly as a source of heat.

In this latter capacity it is made use of in electric-arc furnaces, such as have been developed by Borcher, Moissan, Acheson and others, mainly for metallurgical purposes but also, to a limited extent, for electric steel production (by Stassano).

Because of the great affinity of carbon for oxygen the electrodes, besides being volatilized and dissipated in finely divided solid particles, will suffer a combustion in the ordinary sense of the word in the neighborhood of the arc hearths. The carbon burns to monoxide and dioxide which gases form the flame of the typical carbon arc. The nitrogen of the air seems to play a part, also, in the arc flame, by the formation of cyanogen. (See page 16.)

§ 9. The Use of Electric Arcs for Pyrochemical Oxidizing Processes.

On account of the extraordinarily strong reducing action which is characteristic of incandescent carbon and other oxidizable electrodes, electric arcs between conductors of the first class are not suitable for oxidizing processes, especially in view of the high temperatures prevailing.

Such a process, for example, is the combustion of the atmospheric nitrogen to form nitrous oxide (for production of nitric acid, nitrates, etc.), a process of great technical and commercial importance.

The combination of the nitrogen with the oxygen of the atmosphere is an endothermic reaction which takes place, in any considerable degree, only at very high temperatures and which requires the addition of heat from an external source, such as an electric arc. Carbon electrodes, however, would retard the intended reaction

or suppress it entirely, since they themselves require oxygen for their combustion and would take it from the intermediary product, nitrous oxide. The same is true for metallic electrodes.

However, oxidizing processes of this nature can be readily carried on with the help of electric arcs, if electrodes of conductors of the second class (oxides, fluorides, silicides, borides, etc.) be employed instead of oxidizable electrodes. This has been shown by the author* and verified by W. Nernst. The latter, subsequently, used also, among other means, such an arc † of 61 watts (153 volts, 0.4 ampere) for the production of nitrous oxide and made the remark that "this simple expedient is capable of producing a 3 per cent mixture of nitrous oxide and air." ‡ The oxides, being themselves products of combustion, since they have been formed by the oxidation of the respective metals, thus do not take away and — like the carbon — consume the oxygen of the arc gases. The electrolyte-arc consequently possesses in a high degree the property of oxidizing the gases brought in contact therewith.

These effects occur also, more or less, in arcs between carbons strongly impregnated with conductors of the second class, — usually fluorides — so-called mineralized carbons. The harmful nitrous-oxide fumes developed con-

* "Eine neue Methode zur Ausführung pyrochemischer Reaktionen." Zeitschr. f. Elektrochemie, 1903, p. 162.

† Rasch, German Patents Nos. 117214 and 137788, April, 1899. E.T.Z., 22 (1901), p. 155. Observations of this nature contributed to the author's belief that the practical application of such arcs, despite their great luminous efficiency, were out of the question as sources of light, the more so as this seemed to be made unnecessary by the appearance of the so-called flame lamp (1900) by means of which the same object was accomplished in a kindred manner.

‡ Nernst, "Über die Bildung von Stickoxyd bei hohen Temperaturen." Göttinger Nachrichten, 4 (1904), p. 270.

stitute an unpleasant and unsanitary feature of such arcs for indoor use.

It is especially in the case of long arcs that the formation of nitrous oxide becomes pronounced, because the oxidation of nitrogen can take place in the arc sphere — chiefly consisting of incandescent vapors of conductors of the second class — without being more or less interfered with by the reducing action of the incandescent carbon tips.

To get rid of the nitrous oxide formed in flame carbon arc lamps Gebr. Siemens and others have proposed the introduction into the lamp globes of substances which would combine chemically with the nitrous oxide (for instance, ammonium carbonate).

In general, however, this fixation of the nitrous oxide does not proceed entirely without difficulties nor so simply. This is evident from the difficulties met with in the artificial production of nitrogen compounds.

Even the conversion of the nitrous vapors to potassium nitrate by means of caustic potash (KOH) will take place in appreciable quantities — as Warburg has shown — only when a considerable amount of ozone is present in the gas mixture.

The author has proven* that stable electrolyte-arcs can be maintained at low voltages also within liquids. If the gas mixture which is to be oxidized be blown into a liquid, for example through a hollow electrolyte-electrode, the oxidation products will be immediately removed from the surface of the oxidizing flame by the heat-absorbing liquid and thus will not have time to become decomposed again. A rapid removal from the seat of reaction and condensation of the oxidation products are essential for the efficiency of this and similar processes.

* Zeitschr. f. Elektrochem., 1907, p. 669.

§ 10. Electric Conductivity and Temperature Coefficient.

Although carbon chemically is a simple substance — presumably, however, one of high molecular weight — in some of its allotropic forms it has points of close physical resemblance to substances decomposable by electrolysis, such as colloidal metallic oxides (glass melts) and other nonconductors which we include under the designation "solid conductors of the second class."

This fact is most conspicuous in the case of carbon in its purest, crystallized form, the diamond. While the amorphous carbon in the form of lampblack has nearly the theoretical "black body" absorption for light and heat, diamond is characterized by its exceptionally high refraction index ($n = 2.42$), its transparency and its high reflecting power. The amorphous varieties of carbon (lampblack, graphite, etc.), possess an appreciable electrical conductivity. The diamond, on the contrary, is a nonconductor and like other dielectric substances becomes electrified by rubbing.

Like the dielectrics, the electrical conductivity of carbon increases with the temperature, while the reverse is the case for metals (see page 9). The latter, according to all probability and all available experimental data, possess zero resistivity at absolute zero of temperature ($t = -273°$ C.; $T = 0°$), i.e., the conductivity $\kappa = \frac{1}{r} = \infty$, as indicated on Fig. 15, whereas conductors of the second class possess an infinitely high resistance at this temperature and even at the terrestrial temperature ($T = 291°$), not so far from absolute zero, are spoken of as insulators in the full sense of the word.

While the resistivity (r) of metals increases with temperature, that of conductors of the second class decreases

at an exceedingly rapid rate with ascending temperatures and obviously tends to a limiting value, near zero, for infinitely high temperatures. It is probable that the typical dielectrics, the gases, behave in an analogous manner.

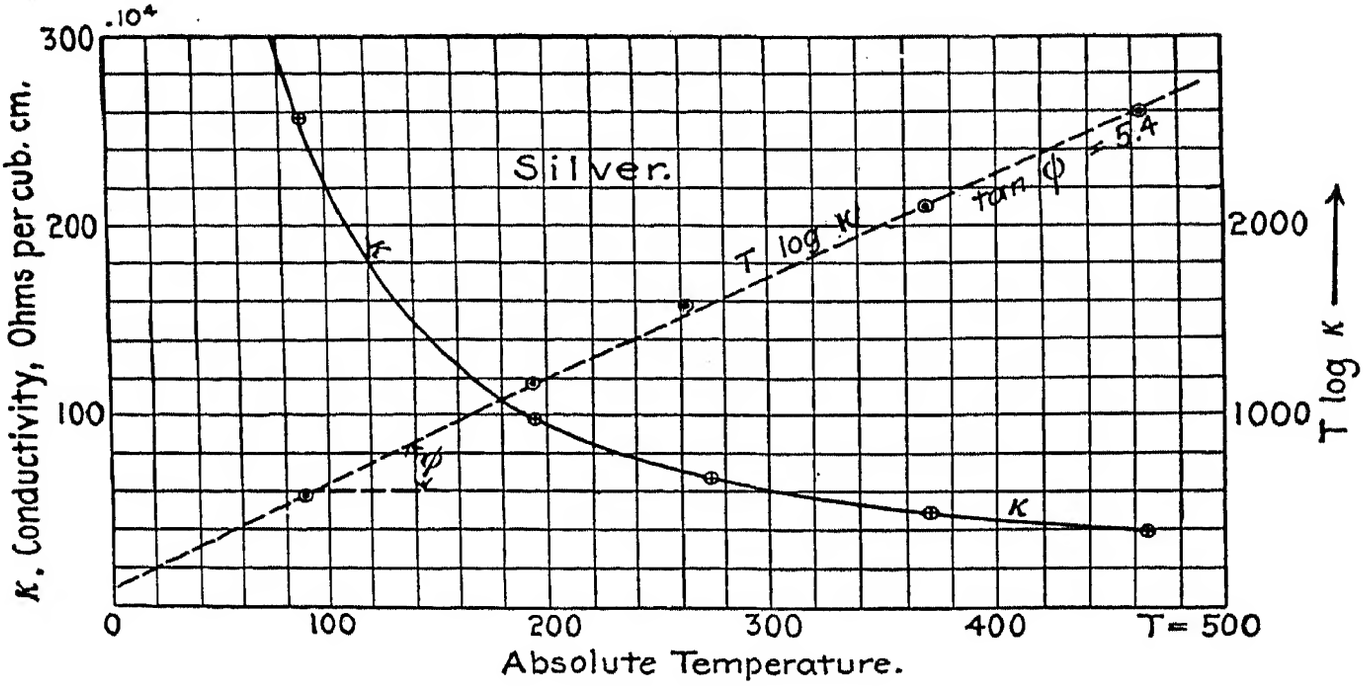


FIG. 15.

While, thus, for metals the temperature coefficient $\left(\kappa = \frac{1}{r}\right)$, i.e., $\frac{d\kappa}{\kappa}\frac{1}{dT}$, is negative, electrolytes and all substances included under the term "conductors of the second class" possess pronounced positive temperature coefficient.

This is also the case with carbon. For carbon, in the modification in which it is deposited from hydrocarbon on glowing carbon fibers in the manufacture ("flashing") of filaments for electrical incandescent lamps — a relatively dense form of carbon with metallic luster — the temperature coefficient, at temperatures around $\pm$ 100° C. and around $t = 0°$ C. has been found to be

$$\alpha = \frac{d\kappa}{\kappa}\frac{1}{dT} = +\,323 \times 10^{-6}.$$

TABLE 2. RELATION OF ELECTRICAL RESISTIVITY (r) TO TEMPERATURE (t) FOR VARIOUS ELECTRODE MATERIALS.

$r = r_0 (1 + at + bt^2)$.

Material.	Temperature, °C.	a.	b.	Authority.
Graphite, sp. gr. = 2.3	25 to 193	−0.00088	.....	Borgmann.
Graphite	25 to 250	−0.00082	.....	Borgmann.
Graphite, Siberian	26 to 302	−0.00074	.....	Muraoka.
Graphite, compressed powder	−77 to + 10	−0.00120	.....	Streintz.
Arc-lamp carbon " a "	25 to 230	−0.000314	.....	Siemens.
Arc-lamp carbon " b "	75 to 200	−0.000301	.....	Siemens.
Arc-lamp carbon " c "	26 to 335	−0.000425	195×10^{-6}	Muraoka.
Arc-lamp carbon " d "	14 to 100	−0.000240	.....	Muraoka.
Arc-lamp carbon " e "	31 to 832	−0.000415	129×10^{-6}	Muraoka.
Anthracite, sp. gr. = 1.654	25 to 152	−0.000350	.....	Borgmann.
Hematite (93.6 Fe_2O_3 + 3.3 FeO + 3.6 TiO_2)	0 to 100	−0.000588	.....	Bäckström.

The values for these temperature coefficients, however, will always be far below those for the electrolytes proper (aqueous solutions). In the latter the temperature coefficients at room temperature are of the order $\alpha = 0.02$ to 0.03; in other words, the conductivity will increase 2 to 3 per cent per degree centigrade rise of temperature, — quite considerably, as will be seen.

If, in accordance with the usual custom, the rate of increase in specific resistance (r) be expressed by the parabolic equation

$$\frac{r}{r_0} = 1 + at + bt^2,$$

the value of the constants a and b for such varieties of carbon as are of interest to us will be found in Table 2 above. In this table has been included also the corresponding values for the mineral (titaniferous) hematite, which is of interest in connection with the magnetite lamp. In the latter is used, to form the arc, instead of carbon, titaniferous oxide of iron the electrical resistivity of which, like that of all typical conductors of the second class, decreases with increase of temperature (α is negative).

With respect to the absolute value, the conductivity of carbon depends on the method of manufacture, fineness of grain, density, etc.; in short, on the "history" of the product. Arc-lamp carbons of the usual kind and process of manufacture have a resistance of 65 ohms per meter of 1 sq. mm. cross-sectional area.

Table 3, below, gives an idea of the specific conductivity (κ) of various forms of carbon and raw materials for the manufacture of carbon electrodes.

TABLE 3. ELECTRICAL CONDUCTIVITY (κ) OF DIFFERENT FORMS OF CARBON.

Material.	Temperature °C.	κ, Conductivity (ohms per cm.^{3}).	Authority
Diamond	15	0.211×10^{-14} to 0.309×10^{-14}	Artom.
Amorphous carbon	12	0.25	Streintz.
Graphite	0	0.0705×10^4	Streintz.
Graphite from Siberia	0	0.0871×10^4	Muraoka.
Graphite from Ceylon	0	0.08×10^4 to 0.39×10^4	Piesch.
Graphite from Greenland	15	0.247×10^4	Artom.
Graphite from Cumberland	15	0.054×10^4	Artom.
Graphite from Siberia	15	0.082×10^4	Artom.
Gas-retort coke			
By Duboscq	0	0.0145×10^4	Siemens.
By Gaudoin	0	0.0204×10^4	Muraoka.
Arc-lamp carbons	0	0.0248×10^4	Muraoka.
By Duboscq	0	0.0305×10^4	Beetz.
By Carré	15	0.0142×10^4	Lucas.
Incandescent-lamp filaments	−182	0.0235×10^4	Dewar and Fleming
	−100	0.0241×10^4	
	+18.9	0.0252×10^4	

The reciprocal value $r = \frac{1}{\kappa}$ is the specific resistance in ohms per centimeter cube.*

* The resistance of a wire of 1 sq. mm. cross-sectional area and 1 meter in length is $\frac{10{,}000}{\kappa}$.

§ 11. Heat Conductivity.

The stability and luminous efficiency of an arc is influenced by the heat conductivity of the electrode material, the more so as the greater portion of the energy developed in the arc is carried off by conduction through the electrodes (Granqvist, see page 6).

If λ is the thermal conductivity* and κ the electrical conductivity † of a substance $n_0 = \frac{\lambda_0}{\kappa_0}$, the ratio of these at a temperature $t = 0°$, and n_{100} the ratio at 100° C., then, according to Lorenz, the following general relation is true for metals

$$\frac{n_{100}}{n_0} = \frac{\lambda_{100} \div \kappa_{100}}{\lambda_0 \div \kappa_0} = \text{constant} = 1.367;$$

that is, $\frac{\lambda}{\kappa}$ is a function of the temperature.

Among metallic substances used for electrodes, mercury has found application in the mercury vapor lamp. The heat conductivity of mercury, between 0 degrees and 300° C., is

$$\lambda = 0.0148\ (1 - 0.00045\, t°) \text{ in cm., g., sec., } ° \text{C.},$$

showing that the thermal, as well as the electrical conductivity, decreases with increase of temperature.

The thermal conductivity of homogeneous carbon (retort carbon) is not of much smaller value,

$$\lambda = 0.0103\ (1 + 0.000012\ t°) \text{ in cm., g., sec., } ° \text{C.}$$

Its temperature coefficient for both thermal and electrical conduction, thus, is positive.

The heat conductivity of non-metallic homogeneous

* λ is the heat, in gram-calories, which will flow per second through each square centimeter cross-section of a plate, 1 cm. thick, when the two sides of the plate differ in temperature by 1° C.

† Electrical conductivity is here referred to mercury = 1.

glasses of metallic oxides is of the order $\lambda = 0.001 - 0.002$,* thus considerably lower than that of carbon.

For insulating substances the thermal temperature coefficient is very small and apparently negative.

According to Winkelmann † the heat conductivity — which always gives an approximate idea of the electrical conductivity — of solid solutions composed of a mixture of metallic oxides can be derived from heat conductivities of the individual oxides, viz: If

p_1, p_2, p_3 are the percentages of the substances 1, 2, 3, . . . and $p_1 + p_2 + p_3 + \ldots = 100$,

$\lambda_1, \lambda_2, \lambda_3 \ldots$ the heat conductivities and

$\gamma_1, \gamma_2, \gamma_3 \ldots$ the specific gravities of the individual substances,

then, the specific volume of each component substance within the solid solution, assuming the latter to be homogeneous like a glass mixture, will be

$$v_1 = \frac{\frac{p_1}{\gamma_1} 100}{\frac{p_1}{\gamma_1} + \frac{p_2}{\gamma_2} + \frac{p_3}{\gamma_3} + \ldots}, \qquad v_2 = \frac{\frac{p_2}{\gamma_2}}{\frac{p_1}{\gamma_1} + \frac{p_2}{\gamma_2} + \frac{p_3}{\gamma_3} + \ldots},$$

or, in generalized form,

$$v_n = \frac{\frac{p_n}{\gamma_n}}{\sum\left[\frac{p}{\gamma}\right]}.$$

The heat conductivity of the resulting solid solution, thus, will be

$$\lambda = \frac{100}{\frac{v_1}{\lambda_1} + \frac{v_2}{\lambda_2} + \frac{v_3}{\lambda_3} + \ldots \frac{v_n}{\lambda_n}}.$$

* For $5\ Al_2O_3 + 71\ SiO_2 + 10\ Na_2O + 14\ B_2O_3$ $\lambda = 0.00227$.
For $79\ PbO + 21\ SiO_2$ $\lambda = 0.00108$.
For feldspar $\lambda = 0.0057$.
For quartz $\lambda = 0.0024$.

† Wied. Ann., 1, 160 (1899).

Winkelmann gives the following values for heat conductivities (λ) and densities (γ) of metallic oxides. (See Table 4).

Experience tends to prove that in general the electrical conductivity κ of non-metallic mixtures increases simultaneously with λ.

TABLE 4. HEAT CONDUCTIVITY (λ) AND DENSITY (γ) OF METALLIC OXIDES.

Material.	Specific gravity γ.	Heat conductivity λ.	$\frac{1}{100\,\lambda}$.
PbO	9.6	625×10^{-6}	16.0
BaO	7.0	769×10^{-6}	13.0
ZnO	5.9	667×10^{-6}	15.0
Al_2O_3	4.1	4000×10^{-6}	2.5
MgO	3.8	2000×10^{-6}	5.0
CaO	3.3	1667×10^{-6}	6.0
K_2O	2.8	753×10^{-6}	13.3
Na_2O	2.6	952×10^{-6}	10.5
P_2O_5	2.55	1493×10^{-6}	6.7
SiO_2	2.30	2943×10^{-6}	3.4
B_2O_3	1.98	1517×10^{-6}	6.6

Thermal conductivity (λ), *radiating power and refraction index* (n) *of carbon and solid conductors of the second class.*

The emissive as well as the reflecting power (R) of a substance is closely related to its refractive index (n).

If R is the reflecting power of a substance, the latter will absorb of the incident light of the same wave lengths the amount

$$A = 1 - R.$$

According to Kirchhoff's law the emissive power for light rays of a given wave length is proportional to the absorptive power, A, for rays of the same wave lengths, both referred to the same temperature conditions.

Approximately, a substance with the refractive index n will reflect of the incident radiation J the amount

$$R = J\left(\frac{n-1}{n+1}\right)^2.$$

The refractive index n is dependent on pressure, temperature and state of aggregation. Thus it will vary with the density, γ. The specific refractive power, approximately expressed by

$$R' = \frac{1}{\gamma}\frac{n^2-1}{n^2+2},$$

on the contrary, is a constant value.

Moreover, it is an additive property; i.e., in the case of mixtures, etc., the individual refractive powers of the ingredients may be added together according to their respective proportions in the mixture.

Practically nothing is known, even experimentally, of the true emissive power of substances. And yet it is in just this direction that the arc-lamp and illuminating engineers will have to seek guidance for the progress towards perfection of illuminants (flame carbon arcs, electrolyte-arcs, magnetite arcs, etc.), by the selection of efficient electrode materials. This can be done at present only by guesswork combined with scientific intuition based on experiences in fields which sometimes may seem to lie quite remote from the problem at hand.

Such data as are available relating to reflective, absorptive and emissive power of materials at low temperatures obviously can be of no use for judging the optical characteristics at high temperatures of the same substances, whether they be in the form of solid incandescent electrode surfaces or vaporized as the gases in the arc flame.

Thus, the known values are not quantitatively trans-

ferable upon high temperatures. However, they are always a guide for the progressive and thinking engineer for a qualitative interpretation of general characteristics and for an intuitive insight into the mechanism of phenomena which have a bearing on electric-light engineering; as such they may be used by him, reservedly, as a basis for his experiments.

TABLE 5. REFRACTIVE INDICES OF VARIOUS SUBSTANCES.

Substance.	Refractive index n.	$R'=\left(\frac{n-1}{n+1}\right)^2$.	$E'=1-R'$.
Silver	0.27	0.33	0.66
Diamond	2.42	0.17	0.83
Carbon, cathode deposit	1.645	0.06	0.94
Carbon, incandescent lamp filaments	1.602	0.05	0.95
Calcium fluoride, CaF_2	1.44	0.032	0.968
Limestone, $CaCO_3$	1.66	0.06	0.96
Quartz, SiO_2	1.54	0.05	0.95
Zircon, ZrO_2+SiO_2	1.93	0.10	0.90
Wolframite, $CaWO_4$	1.92	0.10	0.90
Rutile, TiO_2	2.5–2.759	0.20	0.80
Spinel, $MgAl_2O_4$	1.72	0.07	0.93
Carborundum, SiC	2.78	0.22	0.78
Iron oxide, cryst., Fe_2O_3	2.9–3.2	0.25	0.75
Magnesium fluoride, MgF_2	1.384	0.026	0.974

Table 5 above contains in the last column some values of E' for visible wave lengths, calculated from the expression

$$1-\left(\frac{n-1}{n+1}\right)^2.$$

At high temperatures, in all probability, considerable deviations from these values can occur. It is evident, at any rate, that the value of E' is always high for substances (such as calcium fluoride for example), which in practice have shown themselves as possessing pronounced favorable light radiation characteristics.

It does not seem very likely that black substances, i.e., substances that look dark to the eye, such as carbon, magnetite, carborundum, etc., should possess an especially favorable emissivity within the visible spectrum when used as luminous solids (electrode surfaces).

Nevertheless, with such substances a high degree of luminous efficiency can be attained sometimes — as, for instance, in the magnetite lamp — without taking into account the temperature radiation of the solid substance. However, in these cases the efficiency is due to selective radiation as line and band spectra of the gases in the arc flame (for example, calcium and iron spectra).

While metals, of which silver is a typical representative, are noted for high metallic reflective power and good conductivity (κ), carbon and conductors of the second class, such as calcium fluoride, are characterized by a relatively high absorptive and emissive power.

Among conductors of the second class, magnesium fluoride should prove a good substitute for rutile either in electrodes for magnetite lamps or in the form of mineralized carbons for flame arc lamps.

Magnesia, furthermore, is one of the metallic oxides that cannot be reduced by carbon. Like thoria, it is one of the most refractory substances known. Used as an incandescent electrode surface, it will withstand extraordinary high energy densities and temperatures, and the latter is of paramount importance for economic temperature radiation, i.e., the radiation of a solid.

Obviously, a great many other physical properties require consideration in the selection of substances for use as electrodes.

In general, both requirements — a favorable temperature radiation and suitable selective line and band spectrum of the gases given off in the arc flame — will be simulta-

neously best filled, the higher the boiling point and the dissociation temperature of the substance. In lamps of the mercury vacuum type, however, the temperature radiation of the electrodes is entirely left out of account, and the selective spectral emissivity of the incandescent gases is exclusively depended on as the source of light.

§ 12. Heat Capacity and Radiation.

In forming an opinion of substances intended for the emission of light and, thus, necessarily operated at a high temperature — whether as arc electrodes or as incandescent glowers — their heat capacity, or specific heat (c), deserves especial attention.

The true specific heat at constant pressure is defined as the amount of energy dQ (quantity of heat in gram-calories) necessary to raise the temperature of a body with the mass G — exclusive of any other work done * — by the small increment dT.

Thus

$$c = \frac{1}{G} \times \frac{dQ}{dT},$$

and consequently

$$dQ = c \times G \times dT.$$

The close relation between the specific heat of a luminous layer and the radiation thereof is evident since the efficiency of a luminous body increases rapidly with its temperature.

Roughly, it may be said that the economy of a source

* The work of expansion in overcoming the atmospheric pressure P on the sides of the heated solid as its volume is increased is very small and can be neglected. With gases the case is different. Considerable energy is required to overcome outer pressure P to permit the strong expansion of gases due to heating. A strict thermodynamic analysis of what takes place in the arc is at present lacking, although this problem, from several points of view, would seem to be a most promising one.

of light will be greater, the lower the specific heat c and the smaller the mass $G = s \times V$ (s = specific gravity, V = volume) of the luminous layer, and the greater the radiating surface per unit of mass. These conditions are very favorably filled in Welsbach gas mantles, for example.

Our knowledge of the specific heat of gases is very imperfect at the present time. Yet data on this subject play a rôle — even though one difficult to grasp at first — in the gases of the arc.

According to Le Chatelier * the mean specific heat, referred to constant pressure and absolute temperature T is, per molecule of

Any permanent gas ..... $c_p = 6.5 + 0.0006\,T$;
Carbon dioxide ..... $c_p = 6.5 + 0.0037\,T$;
Water vapor ..... $c_p = 6.5 + 0.0029\,T$.

Our knowledge in regard to the thermal capacity of solids is more extensive, however, and finds application also in connection with electric arcs, for the behavior of which the properties of the hot electrodes is not without importance.

According to Neumann-Kopp's law the specific heat of solid bodies is a distinctly additive property, that is, the molecular heat of a solid compound is equal to the sum of the atomic heats of the elements of which it consists; in other words, it is calculable.

By atomic heat of an element is meant the product of its specific heat and its atomic weight (A). Similarly, the molecular heat is the product of the specific heat of a compound and its molecular weight (M).

Consequently, in chemical compounds (of molecular weight M), of which a number play an important part as the active electrode material for electric arcs of the

* Compt. rend., 104, p 1780 (1887).

second class and for flame carbon arcs, as well as being, in a general way, of interest also for incandescent lamps,

$$Mc = c_1A_1 + c_2A_2 + c_3A_3 + \cdot\ \cdot\ \cdot,$$

in which c_1A_1, etc., are the products of thermal capacity (c) and atomic weight (A) of the individual elements entering into the compound with the molecular weight M and specific heat c.

For a unit of volume ($V = L^3 = 1$) the latent consumption of energy required to raise the temperature of a solid chemical compound (or a solution) having a specific weight s, thus will be

$$\frac{dQ}{dT} = cG = \frac{s}{M}(c_1A_1 + c_2A_2 + c_3A_3 + \cdot\ \cdot\ \cdot) \cdot\ \cdot\ \cdot \frac{\text{g. cal.}}{\text{cm.}^3\ ^\circ\text{C.}},$$

or, expressed in electrical measures (watt-seconds, z),

$$\frac{dQ}{dT} = 0.239 \times \frac{zs}{M}(c_1A_1 + c_2A_2 + c_3A_3 + \cdot\ \cdot\ \cdot) \cdot\ \cdot\ \cdot \frac{\text{watt-seconds}}{\text{cm.}^3 \text{ and } ^\circ\text{C.}}.$$

From this it is evident that, with other things equal, a substance will, *a priori*, be the better radiator the greater its value for

$$\frac{dT}{dQ} = \frac{M}{s}\frac{1}{c_1A_1 + c_2A_2 + \cdot\ \cdot\ \cdot} = \frac{M}{cs},$$

or, in other words, the greater its molecular weight and the smaller its specific heat (c) and specific weight. The atomic heat (cA) for most elements has a value in the neighborhood of 6.3.

A few elements are abnormal in this respect, as will be seen from Table 6.

It is noteworthy and of importance that the specific heat can be calculated for solids (metallic oxides, fluorides, silicides) from the atomic heats also when one of the component elements is a gas as, for instance, oxygen

or fluorine with the same degree of approximation as that of the original Neumann-Kopp's law.

TABLE 6. ATOMIC WEIGHTS AND ABNORMAL ATOMIC HEATS.

Element.	Symbol.	Atomic weight (O=16) *A*.	Atomic heat *Ac*.
Carbon	C	12.0	1.8
Hydrogen	H	1.008	2.3
Boron	B	11.0	2.7
Beryllium	Be	9.1	3.7
Silicon	Si	28.4	3.8–4.8
Oxygen	O	16.0	4.0
Germanium	Ge	72.5	5.5
Fluorine	F	19.0	6.3

The increment in kinetic and potential energy of an atom which corresponds to a temperature rise dT thus is as great for an atom of a gaseous element as for the same kind of atom as a solid in a chemical compound. Furthermore, this increment of energy is approximately the same value for all elements. (Dulong and Petit.)

It can be only briefly pointed out here that this important conformity to law obviously bears a close relation to the radiation phenomena (Stefan-Boltzmann's law) and makes it probable that there is a fundamental law governing both.

In regard to specific heat, also, carbon occupies an exceptional place. The numerical value of its specific heat is relatively high and increases with temperature as shown by curve on Fig. 16.

The theoretical atomic heat of carbon, in accordance with Dulong-Petit's law, requires a value $c = 0.525$ as its specific heat. However, carbon approaches asymptotically this value, only at a high temperature.

It should be noted, also — in agreement with what has been brought out above — that a high value for $\frac{M}{cs}$ is

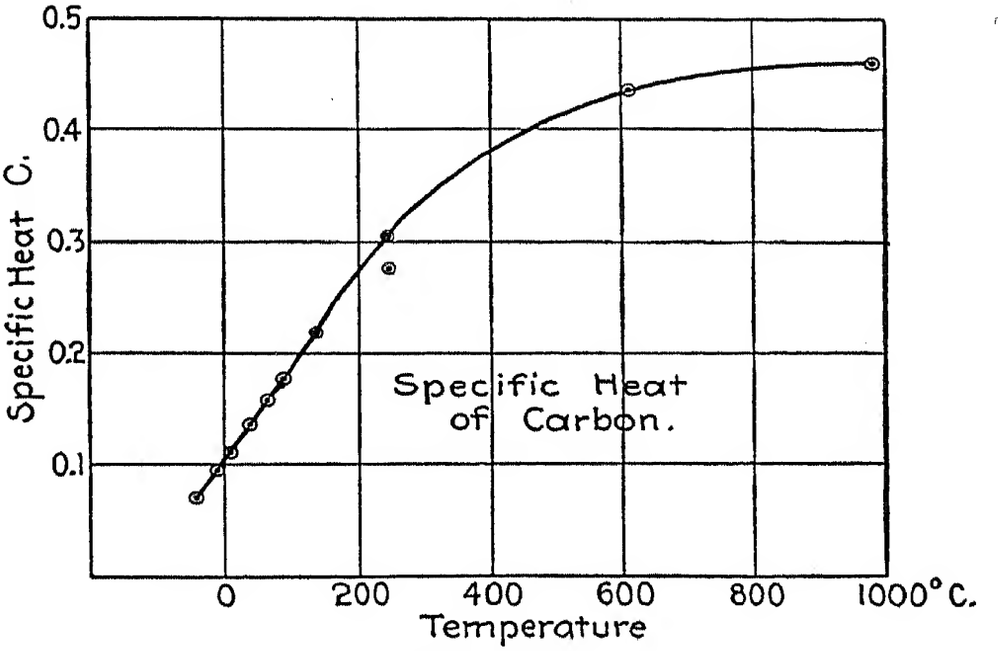


FIG. 16.

possessed by just such metallic oxides (the rare earths), as are used, for their pronounced radiating power, in Welsbach mantles, Nernst glowers and electrolyte-arcs generally. Referring to Table 7, it will be seen that thorium oxide (used in Welsbach mantles) is the highest in this respect.

TABLE 7.

Substance.	$\frac{M}{cs}$ (approx.)	Remarks.
Thorium oxide, Th_2O_3....	950	When pure, very refractory. Sublimes.
Bismuth-trioxide, Bi_2O_3..	935	Very fusible (fluxing material).
Erbium oxide, Er_2O_3.....	677	Gives a greenish tint to the light.
Lanthanum oxide, La_2O_3..	672	
Ytterbium oxide, Yb_2O_3..	665	
Cerium oxide, Ce_2O_3.....	592	Used for Welsbach mantles (about 1 per cent).
Didymium oxide, Di_2O_3 ..	590	
Yttrium oxide, Y_2O_3.....	440	
Tin oxide, SnO.....	211	Fluxing material.
Magnesium oxide, MgO...	(83)	Very refractory.

§ 13. Carbon Electrodes and Their Manufacture.

In lieu of the bulky and fast consuming charcoal electrodes used by Davy, Foucault employed (1843–1844) rods cut out of gas-retort carbon, which material, due to greater density, showed a slower rate of consumption.

Later it became general practice to make the electrodes artificially by compressing powdered carbon, as pure as possible, taking care to avoid contamination by foreign substances. This method of manufacture was adhered to up to the end of the last century.

As raw materials for artificial carbons, gas-retort carbon, petroleum coke and soot are principally used nowadays. As a binder, tar is employed exclusively. The tar, before it can be used, must be de-watered and freed from its volatile contents, after which preparation it should have a specific gravity of 1.2 at 20° C. The binders previously used, such as molasses, sugar, glue and viscous mineral oil, are never used in modern practice.

The raw material is first coarsely broken up in stone crushers and thereafter finely powdered in ball mills. By means of rotary sieves it is then sifted to the proper degree of fineness, after which it is run through a magnetic separator to remove any particles of iron by which it may be contaminated, partly due to wear of the machines in which it has been previously treated.

In kneading machines, of a type similar to the wet mixers manufactured by Messrs. Werner & Pfleiderer, the raw material is then incorporated with the binder. To make this material into a plastic mass roller mills or calender presses with hollow, heated cylinders are usually employed.

After the kneading process the mass must be perfectly homogeneous and free from entrained foreign particles. When cold, the material must be so dry that it can be easily broken up. Up to the most recent time especial stress has been laid on getting the prepared material to contain only the purest form of carbon, and accordingly great pains were taken to avoid any considerable contamination by metallic compounds.

In material for the manufacture of solid carbons it has been the custom to add 0.2 to 0.5 per cent of boric acid. This admixture has been defended as prolonging the life of the carbons and " making the light white."

After kneading, the plastic mass is squirted, by means of an hydraulic press, through nozzles into rods (for solid carbons) or tubes (for cored carbons) and cut off into suitable lengths.

About 100 such rods are tied together into a bundle which is placed, vertically, in a retort and heated to a high temperature (Seger cone No. 12) for from 24 to 48 hours.

This intense burning process is essential, since by this treatment, only, the raw carbons become dense and lose their otherwise great electrical resistivity. Properly prepared carbons have a metallic ring, great hardness and strength and should be of a steel gray color. Poorly calcined carbons introduce an appreciable resistance in the lamp and become more or less heated throughout their whole length, thus dissipating a lot of energy in the form of joulean heat and endangering the lamp parts.

As a general average, one can assume for pure carbon electrodes a specific gravity of 1.472 and a resistance of 65 ohms per meter length of one square millimeter cross-section. (See Table 8.)

TABLE 8. DENSITY AND SPECIFIC RESISTANCE OF THE MORE COMMON BRANDS OF CARBON ELECTRODES.

Name of brand.	Grams per cubic centimeter.	Percentage of ashes in the coreless carbons.	Specific resistance in ohms per meter and square millimeter.
Siemens " A " (Soot carbon) . . .	1.46	0.21–0.47	70
Siemens " T " (Petroleum coke)	1.46	. . . . .	55
Conradty	1.47	0.21–0.64	68
Fuchs (Soot carbon)	1.49	. . . . .	. .
Le Carbone (Soot carbon)	1.48	. . . . .	58
Hardtmuth " F "	. . . .	. . . . .	75
Schiff & Co., " N H "	. . . .	. . . . .	62

§ 14. Rate of Consumption and Dimensioning of Carbon Electrodes.

1. *Oxidation and Consumption.* — Owing to the great affinity of carbon for oxygen the highly heated electrode ends which form the current bases, as well as portions adjacent thereto, will be not only volatilized and dissipated in a finely divided state but, if the supply of oxygen is sufficient, the incandescent carbon particles will be burnt to monoxide and dioxide.

Table 9 gives, according to Zöllner, the rate of consumption with free access of air, of arc-lamp carbons in common use, made by different manufacturers.

The combined consumption of both electrodes amounts to about 0.95 gram of carbon per ampere and hour. For an accurate heat balance of the arc the heat of combustion of the carbons should be taken into consideration. This heat of combustion for artificial arc-lamp carbons is 7706 calories per gram (Sproessner). Thus the heat developed by oxidation of the electrodes figures out to be 0.95×7706 gram-calories per hour and ampere. This corresponds to 8.5 watts in electrical energy.

TABLE 9. RATE OF CONSUMPTION OF CARBON ELECTRODES.

Make.	Arc voltage.	Diameter, millimeters.		Consumption per hour, centimeters.		Amperes.	Consumption per hour, cubic centimeters.			Total consumption per hour and ampere.	
		Solid, −	Cored, +	Solid, −	Cored, +		Solid, −	Cored, +	Total.	cm.³	gms.
Siemens "A"	Continuous current, 55 volts.	11	18	1.58	1.33	8.5	1.50	3.38	4.88	0.575	....
Siemens "T"		11	18	1.30	1.25	8.5	1.24	3.18	4.42	0.520	....
Conradty		11	18	1.22	1.21	8.5	1.16	3.08	4.17	0.490	....
Hardtmuth "E"		11.5	18	1.66	1.28	8.5	1.58	3.26	4.84	0.569	....
									Average:	0.54	.795
	Alternating current, 30 volts.	Cored carbons.		Upper.	Lower.		Upper.	Lower.			
Fuchs, Nouremberg		12		5.6	3.7	16	6.33	4.19	10.52	0.660	....
Schmelzer, Nouremberg		12		8.0	4.5	16	9.04	5.09	14.13	0.884	....
Joos, Stuttgart		12		5.6	5.0	16	6.32	5.65	11.97	0.747	....
									Average:	0.764	1.12

Assuming an arc voltage of 35 volts, the heat delivered by combustion of the carbons will amount, in round figures, to 25 per cent of the total energy developed.

The continual consumption of the material of which the electrodes consist, which, in the case of oxidizable substances — like carbon — and with free access of air, obviously is quite appreciable, makes it necessary to provide manual or automatic means for feeding the electrodes together in order to maintain the arc distance (e_1e_2, Fig. 1) constant. Otherwise the resistance of the gas column which constitutes the arc — and with the resistance the voltage required to maintain the same — will soon increase to values which may exceed the available voltage of the supply net. In other words, the arc would go out.

The regulating mechanism of a lamp, besides serving to prevent the arc from becoming extinguished, has also another function, namely to insure, automatically, the steadiness of the light, which ultimately depends on the conditions of voltage and current.

The lamp mechanism, further, has to start the arc, automatically, when the current is turned on, as well as take care of any moderate fluctuations occurring in the supply voltage which would otherwise cause corresponding fluctuations in the light intensity of the arc.*

2. *Non-symmetrical Burning. Continuous-current Carbons.* — As will be seen by referring to Table 9, the rate of consumption of the anode is considerably greater than that of the cathode, a fact which obviously is a direct result of the nature of the arc, but which, however, for a long time received no definite theoretical interpretation.

This greater consumption of the anode may be explained electrically by a greater voltage drop at the anode than at the cathode and consequently a greater energy density, temperature and luminous radiation.

To maintain the arc in a central position it is customary in alternating-current lamps to employ cored carbons for both electrodes. In continuous-current lamps only the anode is cored and is generally placed above the cathode. (See page 14.) The main object of the axial core is to supply a stream of good conductive vapors from the center of the electrode tip at which point the arc, thus, will tend to stay. For this purpose the core consists of a relatively soft mass of finely powdered carbon with an admixture of boric acid and, eventually, other mineral matter.

The rate of consumption of the upper, positive carbon

* S. J. Zeidler, "Die elektrischen Bogenlampen, deren Prinzip, Konstruktion und Anwendung." There is an English translation of this work.

in continuous-current arc lamps is, on an average, from 2.24 to 2.5 times greater than that of the negative carbon. According to Heims the consumption is

for the positive cored carbon 0.42 cm.^{3} per hour and amp.
for the negative solid carbon 0.17 cm.^{3} per hour and amp.

The total consumption of both electrodes is

in continuous-current lamps 0.8 gram per hour and amp.
in alternating-current lamps 1.12 gram per hour and amp.

3. *Symmetrical Burning. Alternating-current Carbons.* — In alternating-current lamps the burning away of the carbons should, theoretically, be symmetrical, since in such lamps anode and cathode are changing places at each reversal of the current. In reality, however, the upper electrode will consume slightly faster than the lower, which fact can be attributed to the ascending hot-air current.

Both electrodes for alternating-current lamps, therefore, are of the same diameter (D) and cored carbons are always employed.

4. *Dimensions of the Carbons.* — As a general rule, the light distribution and efficiency is better the smaller the diameter of the carbons, in other words, the greater the energy density at the electrode tips.

The increase in ohmic resistance consequent upon decrease in size of the carbons puts a practical limit in that direction, since as a result of the joulean heat developed the electrodes would become too hot, eventually red hot throughout their whole length, and would burn too pointed and attenuated. In consideration of this and to obtain adequate mechanical strength, it is general practice not to make carbons (cored) smaller than

$$D \text{ (in millimeters)} = 5.5 + 4.85\,J \text{ (amperes)}.$$

The light efficiency of the pure carbon arc could be increased not a little if one would adopt the expedient of providing them with a sufficient metallic coating to act as the principal carrier of the current. In the case of carbons containing large percentages of conductors of the second class some such path for the current is imperative.* Even in that case, however, there is a limit to the permissible current density, as it has been found that if the current density exceeds a certain value it will cause " hissing " of the arc.

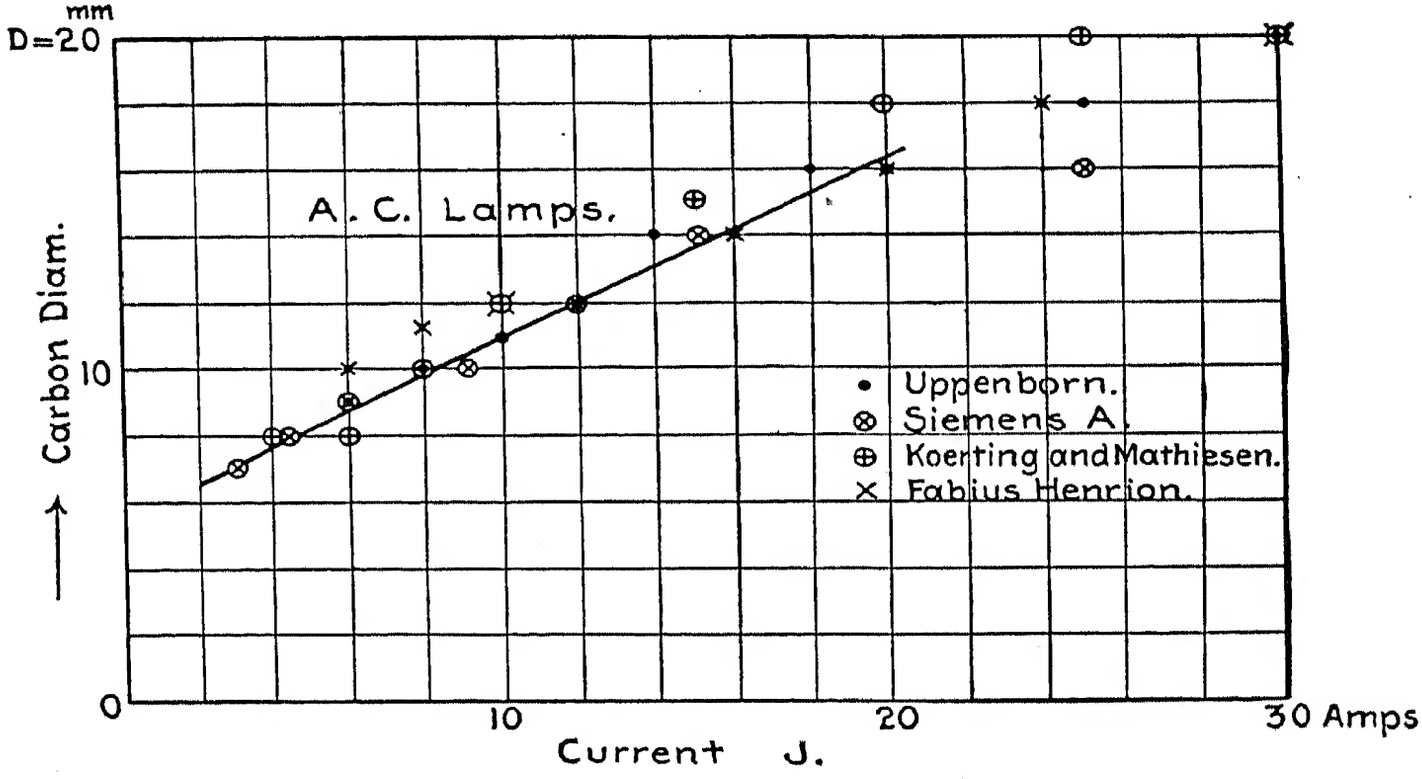


FIG. 17.

The dimensions of carbons for alternating-current lamps as used in general practice is shown graphically on Fig. 17.

For the diameter (d) of the core the following relations, based on practical experience, are generally adopted:

Alternating-current carbons $d = 4.0 + 0.093\,D$.

Continuous-current carbons $d = 1.8 + 0.11\,D$.

* German Patent No. 117214 (1899).

Continuous-current Carbons. — In order to obtain equal linear consumption of the faster-burning positive and the slower-burning negative, lower carbon, the former, which always is a cored carbon, is given a larger diameter, usually according to the relation

$$D_+ = 1.55\, D_-.$$

The negative, solid carbon is chosen of such a size that the current density will not exceed 9 to 10 amperes per square centimeter in the full cross-sectional area of the electrode.

Enclosed Arc Carbons. — In enclosed arc lamps the construction of the lamp mechanism and lamp casing is such that the access of oxygen to the electrodes is purposely restricted and their oxidation, consequently, retarded. This results in a longer life of the electrodes, which in many cases is considered a satisfactory compensation for the about 30 per cent lower light efficiency of the enclosed arc.

Usually, solid carbons are used in enclosed arc lamps, since the centering effect of a core is not needed. (See page 17.) There are, however, examples of different practice, as, for instance, the "Helios" lamp, in which, to obtain more favorable light distribution, is used, for upper electrode, a cored carbon 15 mm. in diameter and, for lower, a solid carbon, 10 mm. in diameter. The rate of consumption of the upper, positive carbon is, in this lamp, about twice that of the lower, negative carbon. The current density is from 2 to 4 amp. per sq. cm. The combined consumption of both electrodes is about 0.25 gram per hour and ampere.

CHAPTER IV.

THE THEORY OF ELECTRICAL DISCHARGES THROUGH GASES.

§ 15. The Ionization of Gases.

ACCORDING to the electronic theory electrical discharges through gases are effected by the motion of free ions which, at ordinary temperature and pressure, exist in gases only to a small extent and generally require the expenditure of a certain amount of energy — the energy of ionization — in order to be changed from the neutral form, in which they are nonconductors of electricity, to the free state, in which they are capable of neutralizing the charges of two condenser plates between which there exists a potential difference $E = E_1 - E_2$.

This neutralization can be either of a disruptive, explosive nature, in which case we speak of it as a spark discharge; or it can be a continuous one. The latter kind includes gas discharges in the ordinary sense.

If the electric current is of low order, i.e., if the transfer of energy is not considerable, one speaks of brush discharges, glow discharges, etc. This is a field which has been the subject of much investigation by experimental physicists, especially in connection with rarefied gases. In case of continuous discharges of larger current values we enter upon the field of ordinary arc and flame arc discharges which have become of the utmost importance for electric-light engineering and high-temperature thermochemistry.

However, in the last few years, the requirements of wireless telegraphy have directed the attention in an in-

creased degree to spark-gap phenomena, so that a brief account of these — which, besides, are closely allied to those of the electric arc — must not be omitted.

Between these two forms of discharge the difference is less one of principle than of the magnitude of current or, in other words, the amount of energy transferred per unit of time.

The work of ionization spoken of above which is necessary to excite any form of electrical discharge is, in ordinary parlance, nothing else than the work that must be done in order to make conductive the normally non-conductive gases between the electrodes e_1 and e_2.

This can be accomplished in several ways:

1. By ultra-violet radiation, Roentgen rays and radium rays, etc., which all possess the property of making a gas through which they pass more or less conductive. (Ionization.)

2. By the dynamic action of an electrostatic field of sufficiently high tension.

3. *a*. By heating of the gases within the discharge space.

b. By heating and simultaneous introduction into the discharge space of conductive gases which may, for example, be generated by flames, more especially by flames in which metallic salts are being vaporized.

The first case comes into practical consideration more rarely. It should be mentioned, however, that this method of starting mercury vapor lamps has been proposed.

The second form of action always takes place in the case of disruptive spark discharges. These will be considered later as much as is necessary for a general understanding of the phenomena which characterize the electric arc.

The third example, the initial starting of the arc by heating of the gases in the discharge path and, in special cases — for instance, arcs between conductors of the second class — the simultaneous preheating of the electrodes, is of paramount importance, practically and theoretically, for arc discharges. Without fulfilling these conditions the formation of an arc is not possible.

The intelligent application and study of this form of arc ignition — by preheating — has, only within the last few years, somewhat cleared up the exceedingly complex phenomena occurring in the formation of electric arcs, as well as adding to our knowledge of the theory of the subject in general.

§ 16. The Dynamics of Disruptive Discharges through Gases.

The exceedingly complex phenomena and conditions of spark discharges have often been the subject of experimental investigations without the latter being capable of giving an answer to, or clearing up, the questions with which we are here concerned. Lately Th. Schwedoff * has offered a theory which not only explains the manifold conditions of the disruptive discharge but permits their mathematical predetermination.

The older views, briefly stated, assume that the velocity of free ions in an electrostatic field is constant and proportional to the field strength and that this velocity is the determining factor in the ionization. A direct action of the electrostatic forces on the neutral gaseous molecule was not acknowledged, or was declared unimportant.

The dynamic theory of Schwedoff corrects these views, maintaining that the ions, in likeness with material

* Th. Schwedoff, "Ballistische Theorie der Funkenentladung." Ann. d. Phys., IV, 19, p. 918 (1906).

bodies under the influence of an electrostatic field, experience, first, an acceleration and, secondly, a frictional resistance depending on the density of the medium which they are to traverse. The derivation of Schwedoff's theory results from a mechanical analogy. A free ion falls in an electric field like a leaden ball in the field of gravitational force, suffering at the same time the resistance of the medium.

The splitting up of the neutral gas molecule into free ions, i.e., the beginning of conductivity of the medium, takes place only after, on the one hand, the field strength and, on the other hand, the kinetic energy, of ions already existing in the gas column have reached sufficient magnitude to dissociate new gas molecules by their combined actions. When once a continuous path of dissociated gas molecules has been established, a turbulent breaking up of new molecules is set up and the spark discharge occurs.

According to the electronic theory a gas molecule consists of two ions which carry the electrical charges $+\epsilon$ and $-\epsilon$ and are held together by a force of a certain magnitude. For their separation, i.e., for the formation of free uncombined ions, a certain work of ionization A_i is necessary, which may depend on the nature of the gas and its thermodynamic state.

If the neutral gas molecule is under the influence of a uniform electrostatic field of strength h the two components thereof, that is, the two gas ions with the charges $+\epsilon$ and $-\epsilon$, will be pulled apart with a force $h\epsilon$, which acts over the distance λ — as yet undetermined — and which thus is capable of doing a work

$$A_s = h\epsilon\lambda,$$

the work of the electrostatic field.

The kinetic energy of a free ion — negative ion — of

mass m and velocity u (the work of ballistic impact) is

$$A_k = \frac{mu^2}{2}.$$

The total work of ionization A_i, thus, is

$$A_i = A_s + A_k,$$

or

$$A_i = h\epsilon\lambda + \frac{mu^2}{2},$$

and therefore

$$\frac{mu^2}{2} = A_i - h\epsilon\lambda.$$

If one imagines an electrostatic field of such a strength H that the work thereof,

$$H\epsilon\lambda = A_i,$$

is sufficient for the total work of ionization A_i, then

$$H\epsilon\lambda = h\epsilon\lambda + \frac{mu^2}{2},$$

$$(H - h)\epsilon\lambda = \frac{mu^2}{2}.$$

An electron (free ion) is now moving in an electrostatic field, is accelerated by $h\epsilon$ and impeded by a frictional resistance due to the gaseous medium and amounting to *

$$f = f_1 u^2 \delta,$$

in which δ is the density of the gas, and f_1 the resistance, referred to velocity $u = 1$ and density $\delta = 1$. From these assumptions Schwedoff deduces the equation for the motion of electrons,

$$m\frac{du}{dt} = h - f_1 u^2,$$

* This is Newton's ballastic equation for the resistance offered by relatively thin media to impacts of relatively high velocity. The employment of this equation in Schwedoff's theory is not free from objection, but does not, however, at first hand, lead to gross discrepancies.

in which t refers to the time. If x is the distance traversed by the electron in the time t, then $\frac{dx}{dt} = u$ is the velocity thereof.

Consequently

$$dx = m \frac{u\,du}{h\epsilon - f_1 u^2 \delta},$$

if δ is the density of the gas referred to air (of normal atmospheric condition and temperature).

If the question be limited to a uniform electrostatic field, i.e., to the consideration of approximately flat disk electrodes, between which the lines of flux pass parallel to each other and normal to the electrode surfaces, the kinetic energy increases with the fall (distance traveled) of the electrons. The maximum value will be attained by those which are able to traverse the whole thickness of the gas layer l (sparking distance) and which therefore are the ones to effect the first neutralization of potential between the electrodes.

Integrating the left side of the above equation between $x = 0$ and $x = l$, the integral of the right side will express the maximum velocity.

Since for $x = 0$ also $u = 0$ we get

$$l = \frac{m}{2\,p\delta} \text{ nat. log} \left[\frac{1}{1 - \frac{p\delta}{\epsilon h} u^2} \right].$$

The maximum kinetic energy possible for a given spark length l and electrostatic field h will then be

$$\frac{mu^2}{2} = \frac{m\epsilon h}{2\,p\delta} \left[1 - e^{-\frac{2\,p\delta}{m} l} \right].$$

Making the factor $\frac{m}{2\,p} = c$,

we get

$$\frac{mu^2}{2} = c\frac{h\epsilon}{\delta}\left[1 - e^{-\frac{l}{c}\delta}\right].$$

In this equation,

c is a linear quantity,
δ is a pure numeral.

Referring to a foregoing equation,

$$\frac{mu^2}{2} = (H - h)\epsilon\lambda,$$

we finally arrive at the ultimate equation

$$\frac{V}{l} = h = \frac{H}{1 + \frac{c}{\lambda\delta}\left[1 - e^{\frac{l}{c}\delta}\right]},$$

by which is determined the relation between spark length l and field strength h necessary for spark discharge.

The theory presupposes a uniform electrostatic field, i.e., that the discharge takes place between plane condenser plates, or between spheres of a diameter which is large relative to the spark gap l.

Experimental data make this dynamic theory of spark discharges seem very probable, especially since by the same we are able to explain the hitherto puzzling fact that relatively far greater field strength is necessary to break down shorter spark gaps than for longer ones, that is, to produce long sparks.

Through the investigations of Earhart, Shaw, G. Liebig, Baille and Freiberg the following values have been obtained for the constants in the above equations. Spark length is expressed in centimeters, discharge potential in electrostatic C.G.S. units.

$H = 6400$ electrostatic units,
$\lambda = 0.0022$ cm.,
$c_1 = 0.0041$ cm.

The constant c_1 is numerically correct only for gases of normal density and temperature. A more general expression for this constant, by Schwedoff, is

$$c = a \log\left(1 + \frac{l\delta}{b}\right),$$

in which

$$a = 0.0043 \text{ cm.},$$
$$b = 0.0008 \text{ cm.}$$

Thus for discharges in air of mean density ($\delta = 1$),

$$c = 0.0043 \log\left(1 + \frac{l \text{ cm.}}{0.0008}\right).$$

Table 10 (on the next page) shows the close agreement between the values as determined experimentally and as arrived at by calculation. This agreement must be pronounced exceedingly good and the values given, therefore, may be used in practical cases with relatively satisfactory accuracy.

As long as the discharge path l is great in comparison with c, the term $e^{-\frac{l}{c}}$ in the denominator will be negligible and the discharge potential may be expressed (since $h = \frac{V}{l}$),

$$V = \frac{Hl}{1 + \frac{c}{\lambda}}.$$

Since H and λ are constants and c, also, is a constant for gases in similar condition, this equation will be represented by a straight line. For large sparking distances l, the theoretical potential curve, thus, will be practically rectilinear, which is in perfect agreement with experience. This circumstance has led to the erroneous general conclusion that the discharge potential is proportional to

the sparking distance, and it has cost considerable labor and time to establish experimentally the peculiar fact that, in the case of very small spark gaps (of the order of $10\mu = \frac{10}{1000}$ mm.), the potential curve shows a distinct "knee" as it approaches the origin.

TABLE 10. RELATION OF SPARK GAP (l) TO DISCHARGE POTENTIAL (V) FOR SPARK DISCHARGES IN A UNIFORM ELECTRIC FIELD.

Spark gap l in cm.	Discharge potential (V) in electrostatic units.					Remarks.
	Calculated.	Experimentally determined by				
		G. Liebig.	Baille.	Earhart.	Freiberg.	
0.0025	1.92	.....	1.90	1.74	.....	To obtain the discharge potential in volts multiply the value for V by 300.
0.0050	2.39	.....	2.51	2.28	.....	
0.0075	2.79	.....	2.81	2.90	.....	
0.0100	3.17	3.26	3.16	3.37	.....	
0.0200	4.65	4.65	4.51	....	.....	
0.0300	6.10	6.19	6.22	....	.....	
0.0400	7.51	8.16	7.32	....	.....	
0.0500	8.89	9.61	8.71	....	.....	
0.0600	10.22	10.82	9.84	....	.....	
0.0700	11.52	11.95	11.20	....	.....	
0.0800	12.77	12.82	12.38	....	.....	
0.0900	14.05	13.79	13.44	....	.....	
0.1000	15.28	15.00	14.70	....	14.48	
0.2000	26.84	26.30	25.54	....	25.13	
0.3000	37.57	37.27	35.35	....	35.57	
0.4000	47.82	47.82	44.74	....	45.55	
0.5000	57.75	57.95	54.42	....	54.31	
0.6000	67.43	67.77	63.82	....	63.53	
0.7000	76.90	77.99	73.78	....	.....	
0.8000	86.22	87.77	84.86	....	81.55	
0.9000	95.39	97.12	94.72	....	.....	
1.0000	104.4	105.58	105.50	....	96.00	
1.1440	117.3	117.4	.....	....	.....	

This peculiar shape of the potential curve, nevertheless, is in strict accordance with the theory, as is shown by Fig. 18, in which the theoretical curve has been plotted together with the observed values (by Earhart).

Thus, the potential curve must not — as has hitherto generally been done — be represented by a straight line which for $l = 0$ cuts the ordinate axis at $E = 300$ volts (approx.). This assumption of a "minimum potential" $E = 300$ volts (approx.), as well as a number of complicated hypotheses invented for the purpose of explaining the flexure of the curve towards zero (such as condensation of gases on the surface of bodies, etc.), thus have become obsolete. Furthermore, the assumption of a minimum potential of 300 volts is hardly borne out by the observed phenomena of the electric arc.

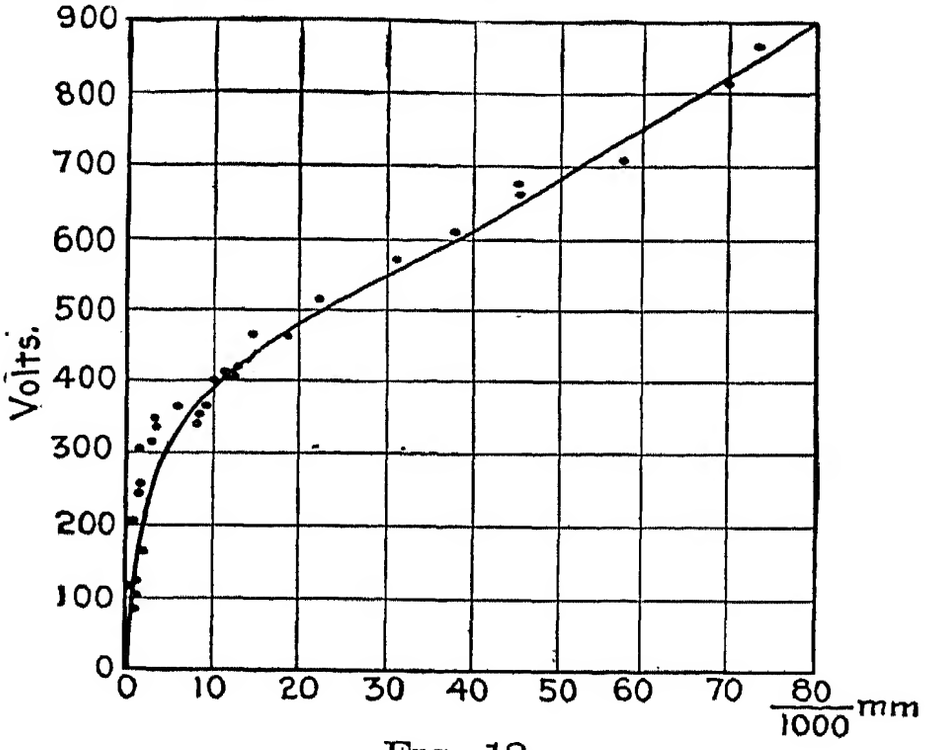


FIG. 18.

Discharge Potential in an Alternating Electrostatic Field. — The above observations are true only for a unidirectional electrostatic field.

In the case of alternating fields, especially those of high frequency, it has been found that the difference of potential at which spark discharge will just take place must always be not only greater, but considerably greater, than for static discharges.*

* J. Algermissen, Ann. d. Phys., 5, pp. 1016 (1906).

CHAPTER V.

SPARK DISCHARGES. EMPIRICAL RESULTS.

§ 17. Spark Discharges between Electrodes of Various Shapes.

In the case of spark discharges between spherical electrodes, and in a still higher degree between needle points, considerable irregularities of behavior take place, which in the main are attributable to the fact that the electric field created is not, even approximately, uniform. Increase of sparking distance, variation of size and shape of the electrodes, as well as a number of other factors, also influence the distribution and paths of the electrostatic lines of force.

On account of the above-mentioned, rather uncertain, physical conditions, a general law of spark-gap potentials — such as governs the discharge potentials between flat plates — can hardly be formulated.

As one example of the complexity of the phenomena may be mentioned that while with a given initial or limiting potential a luminous or silent discharge will take place — glow discharge, brush discharge, etc. — the sudden change of this into an explosive spark discharge appears to be determined by various arbitrary factors (the electrode material, for instance).

In the last analysis this uncertainty can be summed up as follows:

It is consistent with the nature and the name of the disruptive spark discharge that the condenser elements, the electrodes, should lose their charges, and thus their

potentials, abruptly and rapidly; in other words, $\frac{\partial E}{\partial t}$ and $\frac{\partial J}{\partial t}$ become unstable.

Already by this circumstance, it is evident that the measurement of discharge potentials offers exceedingly great difficulties. But besides, and directly connected with the above, a state of equilibrium is reached only after repeated changes of sign of the differential coefficient; or, expressed in plain language, spark discharges are always oscillatory in character. Furthermore, oscillations of this nature are conditioned by the capacity and the self-induction of the circuit. Being based on empirical formulas, the predetermination of the conditions necessary for disruptive discharges—such as are required for wireless telegraphy for example — can, therefore, at best, be only approximate.

§ 18. Symmetrical Arrangement of the Electrodes.

1. *Spherical Electrodes.* — If the discharge takes place between electrodes, symmetrical as to arrangement and size, and if, further, the distribution of potential with respect to the electrodes also is symmetrical, then the first transfer of energy will be in the form of brush discharge — which may change, abruptly, into a spark discharge due to a number of causes — at a starting potential (E_1) for which M. Toepler gives the empirical equation

$$E_1 = 600\, d\left(96 + \frac{64}{\sqrt{d}}\right)\frac{l + d}{l + 5.8\, d} \quad \cdots \text{ volts.}$$

In this l is the shortest distance between, and d the diameter of, the spherical electrodes, both in centimeters. Toepler's formula does not hold true when $\frac{l}{d} < 1$. As

long as $\frac{l}{d}$ is relatively small (more than 1 but less than 6) the spark potential will be the same as the starting potential E_1. When a silent discharge (brush discharge) takes place between electrodes only a short distance apart, it is likely soon to change into a spark discharge. But the chances for such a change diminish rapidly as the electrode distance increases to $\frac{l}{d} > 6$ to 25, the arrangement of the electrodes being symmetrical.

In Table 11 are given values for spark potentials as determined by Freiberg, Heydweiller and Algermissen. These determinations agree fairly well as regards the order of magnitude. Some of the individual values are not inconsiderably at variance, as is generally the case in tests of this kind. Such discrepancies may be attributed to dissimilarity in the test arrangements as well as to differences in the temperature and the atmospheric pressure prevailing during the tests — all of which variables can have considerable influence on the results.

2. *Discharges between Points.*—When two pointed electrodes of diameter d are a considerable distance l apart, making the value $\frac{l}{d}$ large, it is very probable that the spark paths (Fig. 19) coincide with the shortest lines of force, but, at any rate, are not affected by the electrostatic pull in the same degree as are the spark paths between spherical electrodes. This pull acts transversely to the straight connecting lines into which the electrostatic lines of force contract themselves.

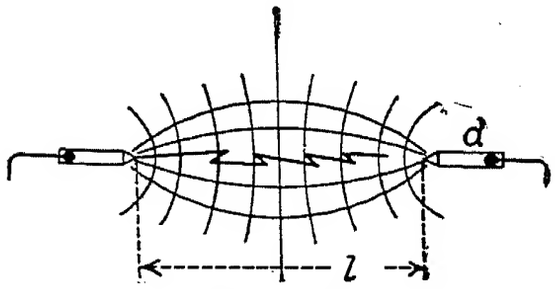


FIG. 19.

It is reasonable to expect physically more clear-cut re-

lations for this form of discharge, and experimental results bears this out.

TABLE 11. STATIC SPARK POTENTIAL FOR LARGER SPARK GAPS.

Discharges between spherical electrodes of radius r.

Radius of spheres.	Discharge potential in volts$\times 10^{-4}$ for spark gaps of l centimeters.				Authority.
	l=1.0	l=1.5	l=2.0	l=2.4	
r=0.5 cm....	2.58	2.95	3.54	3.72	Freiberg.
	2.70	3.17	3.42	3.57	Heydweiller.
	2.70	3.25	3.60	3.80	Algermissen.
Average...	2.66	3.12	3.52	3.70	
r=1.0 cm....	3.27	....	....	....	Freiberg.
	3.57	4.02	4.55	4.85	Heydweiller.
	3.55	4.05	4.85	5.30	Algermissen.
Average ...	3.46	4.035	4.70	5.07	

Radius of spheres.	l=1.2	l=2.0	l=3.0	l=4.5	Authority.
r=2.5 cm....	3.8	5.77	7.30	8.6	Voigt.
	3.8	5.80	8.05	10.1	Algermissen.
Average...	3.8	5.785	7.07	9.35	

The discharge potential E_1 in kilovolts is given by the empirical equation

$$E_1 = a\sqrt{l} + bl.$$

This does not agree with Schwedoff's theory inasmuch as for $l = 0$ it gives $E_1 = 0$.

Toepler gives for the constants the values

$$a = 8.90,$$
$$b = 4.779,$$

when l is centimeters and E_1 is kilovolts.

Referring to Fig. 20 it will be seen that the graph of E_1 shows so small curvature towards the l-abscissa that for

longer spark gaps, somewhat of the order $l = 10$–50 cm., there can practically be substituted for the above equation (with an approximation of $\pm$ 1.5 per cent) B. Walter's * linear interpolation formula,

$$E_1 = 18.0 + 5.75\, l, \quad \ldots \text{ kilovolts.}$$

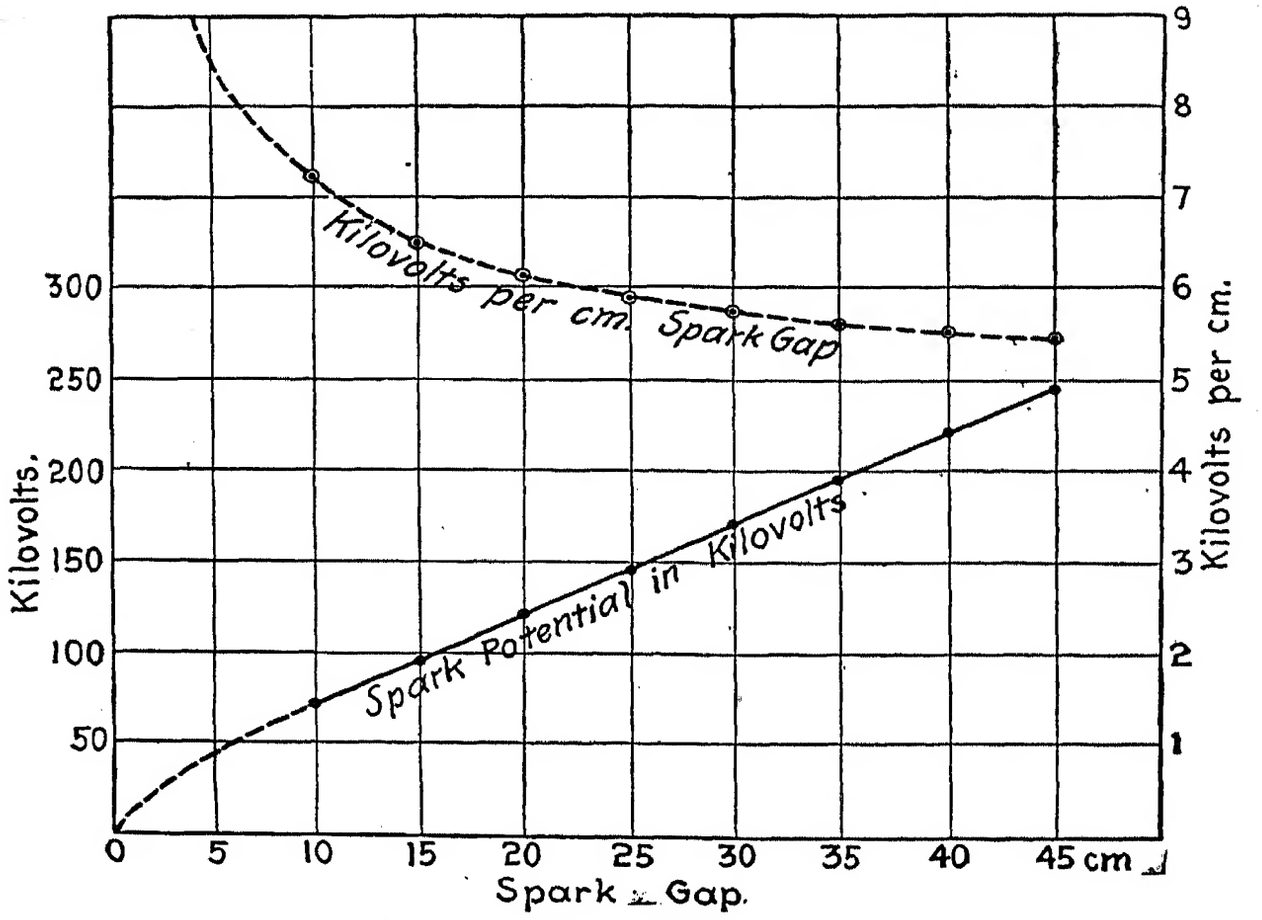


FIG. 20.

As shown on Fig. 20, the spark potential per unit length of spark gap (field strength) decreases with increase of spark gap (l) and approaches asymptotically (for $l = \infty$) a final limiting value which, taking the value $b = 4.779$ kilovolts, as used in the first, more accurate equation, will be = 4779 volts.

In Table 12 are given some additional experimental data obtained by different physicists.

* E.T.Z., 1904, p. 874; W. Vöge, Ann. d. Phys., 14, p. 565 (1904); W. Weicker, E.T.Z., 1904, p. 948.

TABLE 12. SPARK DISCHARGES BETWEEN POINT ELECTRODES.

Authority.	Alternating current. Discharge potential in kilovolts for spark gap of l centimeters. $l=$								Remarks.
	10	15	20	25	30	35	40	45	
A.I.E.E.	73.5	97.8	122.0	146.0	170.0	194.8	.....	.....	
B. Walter	65.8	89.1	111.4	133.6	157.0	176.6	196.4	217.2	
W. Voege	73.2	96.5	119.9	140.6	165.7	190.9	.....	.....	
W. Weiker	(64)	(76)	(98)	(120)	(142)	.....	.....	.....	
M. Toepler	75.9	106.2	135.4	164.0	192.1	219.9	247.5	274.8	
Average	72.1	97.4	122.2	146.1	171.2	195.6	(222)	(246)	
Kilovolts per cm. spark gap	7.21	6.50	6.11	5.85	5.71	5.59	5.55	5.47	

3. *The Dielectric Strength of Air.* — According to another view,* differing considerably from the dynamic theory of spark discharges, the air space between two electrodes possesses a certain dielectric strength. To puncture such a layer of air one centimeter thick by an electric spark requires, as in the case of puncturing a glass plate, a certain maximum value R_{max} for the potential difference between the electrodes.

According to A. Russel

$$R_{max} = \frac{V}{x} f = \text{const. KV. (kilovolts).}$$

If r = radius of spherical electrodes,

x = the distance between centers of spheres,

then for nongrounded electrodes,

$$f = 1 + \frac{11\,r}{32\,x} - \frac{3\,r^2}{256\,x^2} + \frac{11\,r^3}{256\,x^3},$$

$+\frac{V}{2}$ = the potential of one electrode,

$-\frac{V}{2}$ = the potential of the other electrode.

* A. Russel, Proceed. of the Phys. Soc. of London, 20, p. 237 (310). Four illustrations.

If one of the electrodes has the potential V and the other is grounded, then, according to Russel,

$$f_1 = \frac{r}{x} + \frac{1}{\frac{x}{r}+1} + \frac{1}{\left(\frac{x}{r}+1\right)\left(\frac{x}{r}+2\right)^3}.$$

Applying equation (1) to the experimental data previously obtained, Russel found it necessary to subtract 0.8 kilovolt from V in order to obtain agreement, and thus

$$R_{max} = \frac{V - 0.8}{x} f.$$

The degree of agreement of this expression with experimental facts is shown in Tables 13 and 14.

TABLE 13. DIRECT-CURRENT DISCHARGES BETWEEN SPHERICAL ELECTRODES.

Diameter of the spherical electrode.	Authority.	R_{max} in kilovolts.	Remarks.
5 centimeters	J. Algermissen	37.0	Average 38.4 kilovolts.
5 centimeters	A. Heydweiller	37.5	
Slightly convex surfaces	Lord Kelvin	40.8	
1 centimeter	E. Hospitalier	42.2	
1 centimeter	J. Joubert	42.8	
2 centimeters	Cr. Carey Foster	42.9	

The average of the first three values in Table 13 which Russel probably has reason to consider the more accurate is

$$R_{max} = 38{,}400 \text{ volts.}$$

The results obtained with alternating current, a few of which are given in Table 14, show that there is not a very great deviation from those obtained with direct current. If values Nos. 1 and 5 be excluded, as has been done by Russel, we get for alternating-current spark discharges

$$R_{max} = 38.2 \text{ kilovolts,}$$

a value which shows good agreement with corresponding value for direct current (38.4 kilovolts).

TABLE 14. ALTERNATING-CURRENT DISCHARGES.

No.	Electrodes.	Diameter, cm.	Authority.	R_{max} in kilovolts.	Remarks.
1	Cylinders	2.8	C. P. Steinmetz	34.0	
2	Spheres	2.0	Co. de l'Industrie Electr., Geneva	37.9	
3	Spheres	5.0	C. P. Steinmetz	37.8	
4	Cylinders	0.8	C. P. Steinmetz	38.8	
5	Spheres	2.5	C. P. Steinmetz	41.3	

CHAPTER VI.

VOLTAGE AND CURRENT CONDITIONS IN THE ARC.

§ 19. Volt-ampere Characteristic of the Arc.

THE electrical resistance of an arc of the length L is not independent of the current as is the resistance of a metallic conductor at constant temperature. In other words, Ohm's law cannot be applied directly to electric arcs or similar gas discharges.

This becomes evident if one considers how rapidly the specific conductivity of solid, liquid or gaseous conductors of the second class increases with the temperature or with the energy density prevailing in these media and therefore with the strength of the current. It is obvious that the glowing gas column through which the current is conducted from one arc base to the other will, like an ordinary flame, undergo alterations in geometrical shape and cross-sectional dimensions as a result of any change dL in the length of the arc, as well as by increase in current J — alterations which bear no direct relation to electrical quantities. Another consideration is that the size of the current bases on the anode and cathode also varies with change in current and distance between the electrodes, and that the physical properties of the electrode material and the arc gases supplied from this (by variation in conductivity) further complicate the phenomena.

Nevertheless, it is possible to get an understanding of the electrical conditions in the arc, sufficient for practical use, through general relations.

If an arc of constant length L mm. (Fig. 21) be produced between electrodes connected to a constant voltage E, in series with an external resistance of R ohms (consisting of steadying resistance and the resistance of leads and electrodes), a current of J amperes will flow through the circuit. This current will depend on the amount of external resistance as well as on the voltage drop e at the electrode tips. If by reducing the series resistance the current of an arc of constant length be increased by an amount dJ, the arc voltage will drop; vice versa, if the current be decreased the arc voltage e will rise. Sylvanus Thompson expresses in a general form this interdependence by the differential equation *

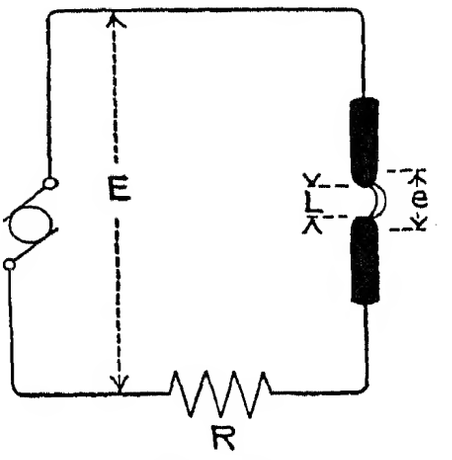


FIG. 21.

$$\frac{de}{dJ} = -\frac{C'}{J^2} (L = \text{constant}). \qquad (1)$$

Integrating this we get

$$e = -C' \int \frac{dJ}{J^2}, \qquad (2a)$$

$$e = m' + \frac{C'}{J}. \qquad (2b)$$

C' is constant as long as the arc length L is not materially changed. The value of C' — and of the voltage drop of the electrodes — obviously must be greater the greater the amount of energy expended to produce the arc flame vapors which form the medium for the current filaments. In other words, C' depends upon the chemical nature and the temperature of the electrode material from which these vapors are generated.

Furthermore, it is evident from purely geometrical

* The Electrician, 29, p. 460 (1892).

considerations that the voltage drop e, and thus also C', must increase with increase of arc length L.

The integration constant m' follows from the fact that for $J = \infty$, i.e., practically, for very powerful arc discharges, the difference of potential, e, or the electrical work done, eJ, cannot be zero; a minimum voltage of finite value, m' (volts), must necessarily exist.

According to Hertha Ayrton, whom principally we have to thank for most of our accurate knowledge of the carbon arc, the minimum voltage m' is greater the longer the arc L'.

For direct-current arcs H. Ayrton gives the following relations (referring to solid carbons, the upper 11 mm., and the lower 9 mm., in diameter):

$$m' = g + \alpha L' = 38.88 + 2.074\, L', \tag{3}$$

$$C' = \gamma + \delta L' = 11.66 + 10.54\, L'. \tag{4}$$

From these she arrives at the general equation

$$e = g + \alpha L' + \frac{\gamma + \delta L'}{J} \text{ (volts, millimeters, amperes)}. \tag{5}$$

This equation represents a system of asymmetrical hyperbolas, as shown in Fig. 22.

We see from this that for all values of L' when $J = 0$ the arc voltage tends towards a value $e = \infty$, and that for increasing current J or decreasing arc length L' the arc voltage approaches asymptotically a value $e = m'$.

With increase of arc length L' the parameter also increases, the radius of curvature becomes greater and the curves, besides, give ever higher values for e.

The constant g, which is independent of current and voltage, is the sum of two quantities, viz., a considerable positive drop of potential, e_1, at the anode and a negative drop, e_2, at the cathode. In the case of plain carbon

electrodes the anodic drop is many times greater than the cathodic.

For the latter Uppenborn (referring to 12-mm. carbons and 6- to 16-mm. arc lengths) has found the value $e_2 = 5.5$ volts; Sylvanus Thompson gives the value $e_2 = 2.5$ volts.

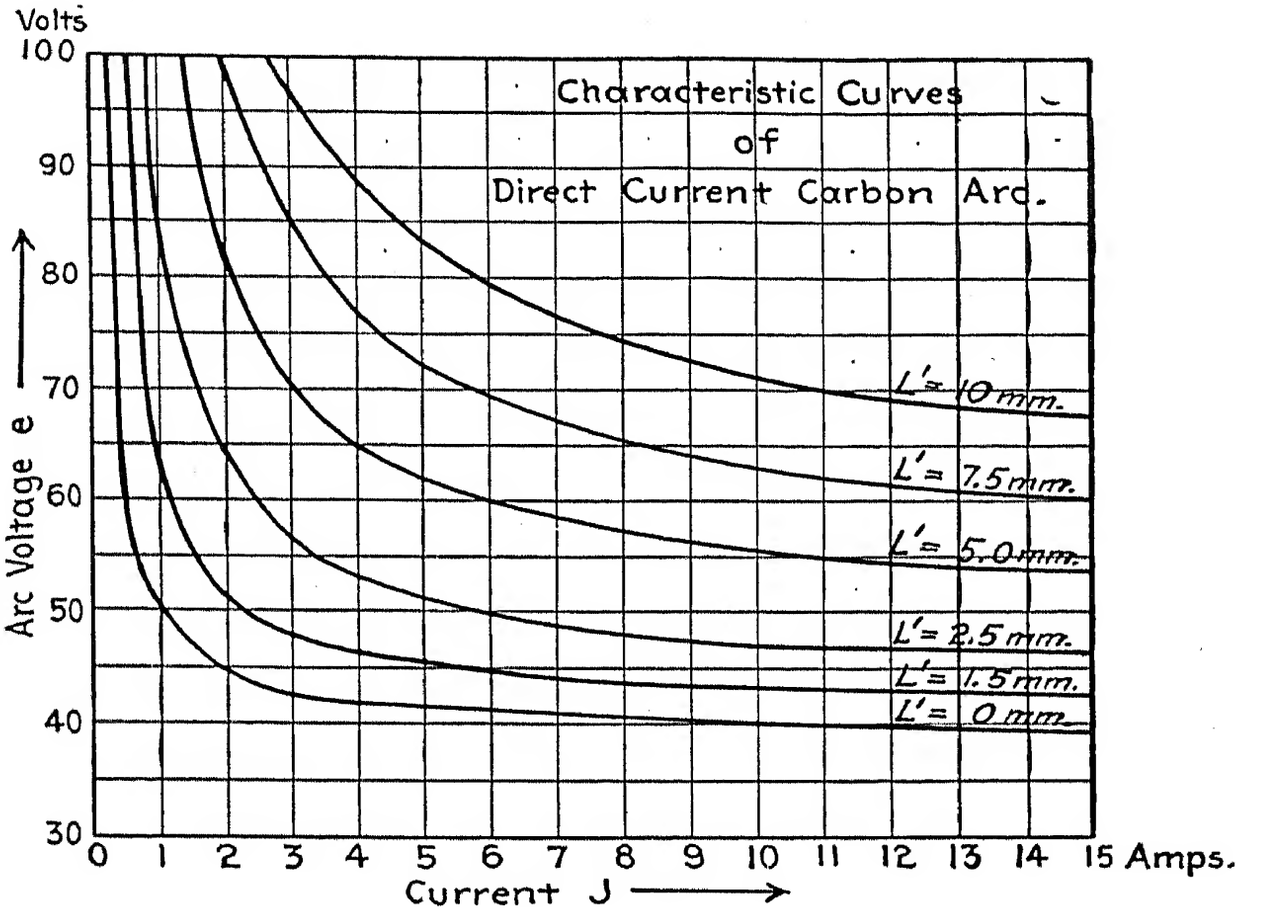


FIG. 22.

It has been shown in the case of normal arcs between pure carbon electrodes that the energy ($e_1 J$ watts) dissipated at the positive current base — the crater surface — constitutes the greater part of the work done in the arc, whereas the energy transformed at the cathode ($e_2 J$ watts) is comparatively small. Corresponding to this, the greater portion, by far, of the light given out proceeds from the anode crater.

The constant α (equation (3)) increases with the arc length but is independent of the current. According to

Hertha Ayrton, α signifies the drop of potential inside the current-carrying gas column.

The energy transformed in the gas column of a pure carbon arc thus would be

$$\mathfrak{A}_2 = \alpha L' J, \text{ . . . watts,}$$
$$(\alpha = 2.074).$$

If we compare this value, $\mathfrak{A}_2 = 2.074\, L'J$, with the energy dissipated at the current bases of the electrodes, $\mathfrak{A}_1 = 38.88\, J$, we will find that for arcs of the usual lengths, between pure carbon electrodes, the amount of energy dissipated in the glowing gases,

$$\mathfrak{A}_2 = \mathfrak{A}_1 \frac{\alpha}{g} L' = 0.072\, \mathfrak{A}_1 L', \text{ . . . watts,}$$

is very small. For arc length $L' = 1.4$ mm. the energy consumed in the arc amounts to only about 10 per cent of that which is radiated by the incandescent electrode ends (cf. page 14 and following).

The constants γ and δ, according to Hertha Ayrton, represent potential losses of a character not nearer specified physically, which are supposed to take place at the electrode ends.

From equations (3) and (4) it is evident that $m' = g + \alpha L'$ and $C' = \gamma + \delta L'$ are connected by a linear relation as shown in Fig. 23. In this C' values have been used for ordinates and m' values for abscissas of the arc-length curve L' (in millimeters). The values for C' and m' in equation (2b) corresponding to any desired arc length L' thus may be found from Fig. 23 by reading the ordinates C' and abscissas m' of the point on the curve L' which represents the arc length in question.

By differentiation of equations (3) and (4) we obtain

$$dC' = \delta\, dL,$$
$$dm' = \alpha\, dL,$$

and thus find

$$\frac{dC'}{dm'} = \frac{\delta}{\alpha} = \text{const.} = \tan \phi, \tag{6}$$

where $\tan \phi$ is the tangent of the straight-line curve in Fig. 23. The numerical value thereof based on Hertha Ayrton's experimental data is

$$\tan \phi = p = \frac{10.54}{2.074} = 5.08.$$

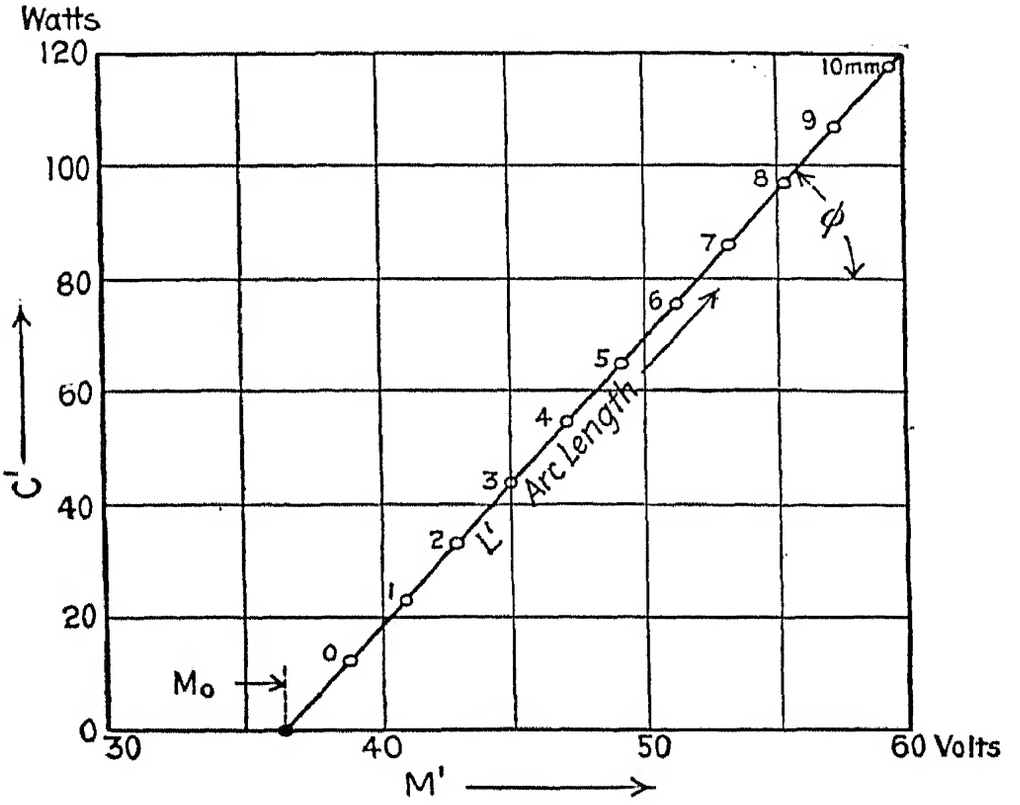


FIG. 23.

C' then becomes

$$C' = p\,(m' - m_0) = 5.08\,(m' - m_0), \tag{7}$$

where $m_0 = 36.6$ volts.

If we write the equation (2b) as follows:

$$eJ - m'J = J\,(e - m') = C', \tag{8}$$

it will be apparent that C', being the product of the current J and the voltage $(e - m')$, represents the electrical work done in watts.

Hertha Ayrton's equations (3 to 5, page 72) are open to the objection that they unnecessarily complicate and do not, as will be made evident below, quite correctly describe the physical relations concerned.

As indicated in Fig. 23, the straight-line curve C' cuts the abscissa at $m_0 = 36.6$ volts. This value plainly is the true minimum potential which must exist at the electrode ends when $J = \infty$, or in other words the arc length $L = 0$, if by separation of the electrodes (contact starting) an arc is to form.

The statement implied by Hertha Ayrton's equation that this occurs when the arc length is less than zero certainly will require to be qualified physically. That Hertha Ayrton's figure for minimum potential, 38.88 volts, is too high is evident, also, from the fact that with three lamps in series on a 110-volt circuit, as is common practice, each lamp burns with 36.6 volts or less.

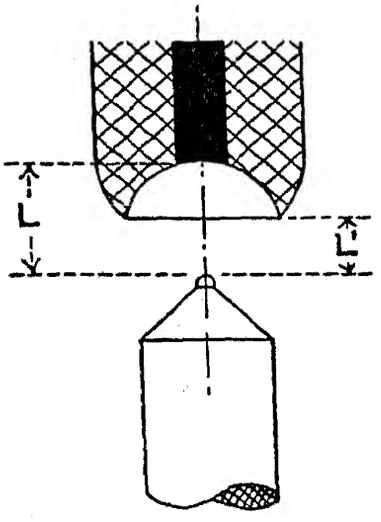


FIG. 24.

This discordance is due to the unsuitable method of measuring the arc length as well as to an objectionable definition thereof.

Usually, like Hertha Ayrton, one denotes and measures as length of the arc the axial distance L' (Fig. 24) between the edge of the anode crater and the point of the cathode. In reality, however, the true length of the arc L, i.e., the length of the current-carrying gas column, is longer by an amount h, namely the depth of the crater. From equation (5) it follows that

$$(e - g)\,J - \alpha L'J = \gamma + \delta L'.$$

A current $J = 0$, which, with a finite value E of the impressed voltage, corresponds to an electrical work

$eJ = 0$ watts, according to Hertha Ayrton's equation, would correspond to an arc length

$$L' = -\frac{\gamma}{\delta} = -\frac{11.66}{10.54} = -1.10 \text{ mm.},$$

a physical impossibility. Obviously for $eJ = 0$ the true length of arc L should also be $= 0$.

The latter thus is

$$L = L' + \frac{\gamma}{\delta} = L' + 1.10.$$

The introduction of the true arc length L results in the following correction and simplification of Hertha Ayrton's equation.

$(g = 38.88;\ \alpha = 2.074\cdot\ \gamma = 11.66;\ \delta = 10.54.)$

$$e = g + \alpha\left(L - \frac{\gamma}{\delta}\right) + \frac{\gamma + \delta\left(L - \frac{\gamma}{\delta}\right)}{J},$$

$$e = g - \frac{\alpha\gamma}{\delta} + \frac{\gamma - \gamma + \delta L}{J},$$

$$e = 36.59 + \alpha L + \frac{\delta L}{J},$$

or, numerically,

$$e = 36.59 + 2.074\,L + \frac{10.54\,L}{J}.$$

For $L = 0$ thus there follows a minimum voltage,

$$m_0 = g - \frac{\alpha\gamma}{\delta} = 36.59 \text{ volts},$$

and for $J = \infty$ the asymptotic potential

$$e = 36.59 + 2.074\,L.$$

The general equation, from which H. Ayrton's constant $\gamma = 11.66$ can be eliminated, thus becomes

$$e = m_0 + \alpha L + \frac{\delta L}{J},$$

$$e = m_0 + L\left(\alpha + \frac{\delta}{J}\right) \text{(volts, millimeters, amperes)}, \quad (9)$$

from which, using H. Ayrton's formulas and coefficients, we obtain the following numerical values of the constants:

$$m_0 = 36.59,$$
$$\alpha = 2.074,$$
$$\delta = 10.54.$$

H. Ayrton's formula thus assumes that the depth h of the anode crater is, practically, 1.1 mm. In reality the value of h is not entirely independent of the arc length and the current.

In Table 15 (on the next page) are given the values of arc characteristic constants for a number of electrode materials compiled from the latest experimental results.*

For very long direct-current arcs between artificially cooled electrodes, such as have found practical application in recent times for electrothermic oxidation of air (see § 9, page 26, and following), A. Grau † has arrived at the following relation, covering a range of $L = 10 - 50$ mm. and $J = 4 - 10$ amps.

$$e = 55 + 125\,L + \frac{900\,L}{J}.$$

Max Toepler ‡ has called attention to the fact that electric arcs of this type, in which the middle portion of the arc is artificially freed from electrode vapors, are comparable to brush discharges and thus obey, also, the formula

$$e = A + \frac{B}{\sqrt{J}}L.$$

* Phys. Zeitschr., 8, 703 (1907).
† Ibid., 9, 107 (1908).
‡ Ibid., 9, 372 (1908).

TABLE 15. CONSTANTS OF ARC CHARACTERISTICS FOR VARIOUS ELECTRODE MATERIALS.

Electrode material.	Authority.	The constants in equation $e=g+\alpha L'+\frac{\gamma+\delta L'}{J}$.				Arc voltage for $J=1$ and $L=1$.	Remarks.
		g.	α.	δ.	γ.		
							Solid carbons.
Carbon.....	H. Ayrton	38.88	2.074	10.54	11.66	63.1	Diam. of positive 11 mm. Diam. of negative 9 mm.
Silver.....	C. E. Guye and L. Zebrikoff (1907)	14.19	3.64	19.01	11.36	48.2	Condition of tests: Current varying between 2 and 18 amps.; arc length between 0 and 2–4 mm.; diam. of electrodes, 16 mm.; electrode tips, flat parallel surfaces.
Iron.....		15.73	2.52	15.02	9.44	42.7	
Nickel.....		17.14	3.89	17.48	.....	38.5	
Cobalt.....		20.78	2.05	10.12	2.07	35.0	
Gold.....		20.82	4.62	20.97	12.17	58.6	
Copper.....		21.38	3.03	15.24	10.69	50.3	
Palladium.....		21.64	3.70	21.78	.....	47.1	
Platinum.....		24.29	4.80	20.33	.....	49.4	

The relationship between arc voltage (e), current (J), and arc length (L) can be illustrated more comprehensibly than by hyperbolas (as in Fig. 22) by means of straight-line curves constructed as shown in Fig. 25. In

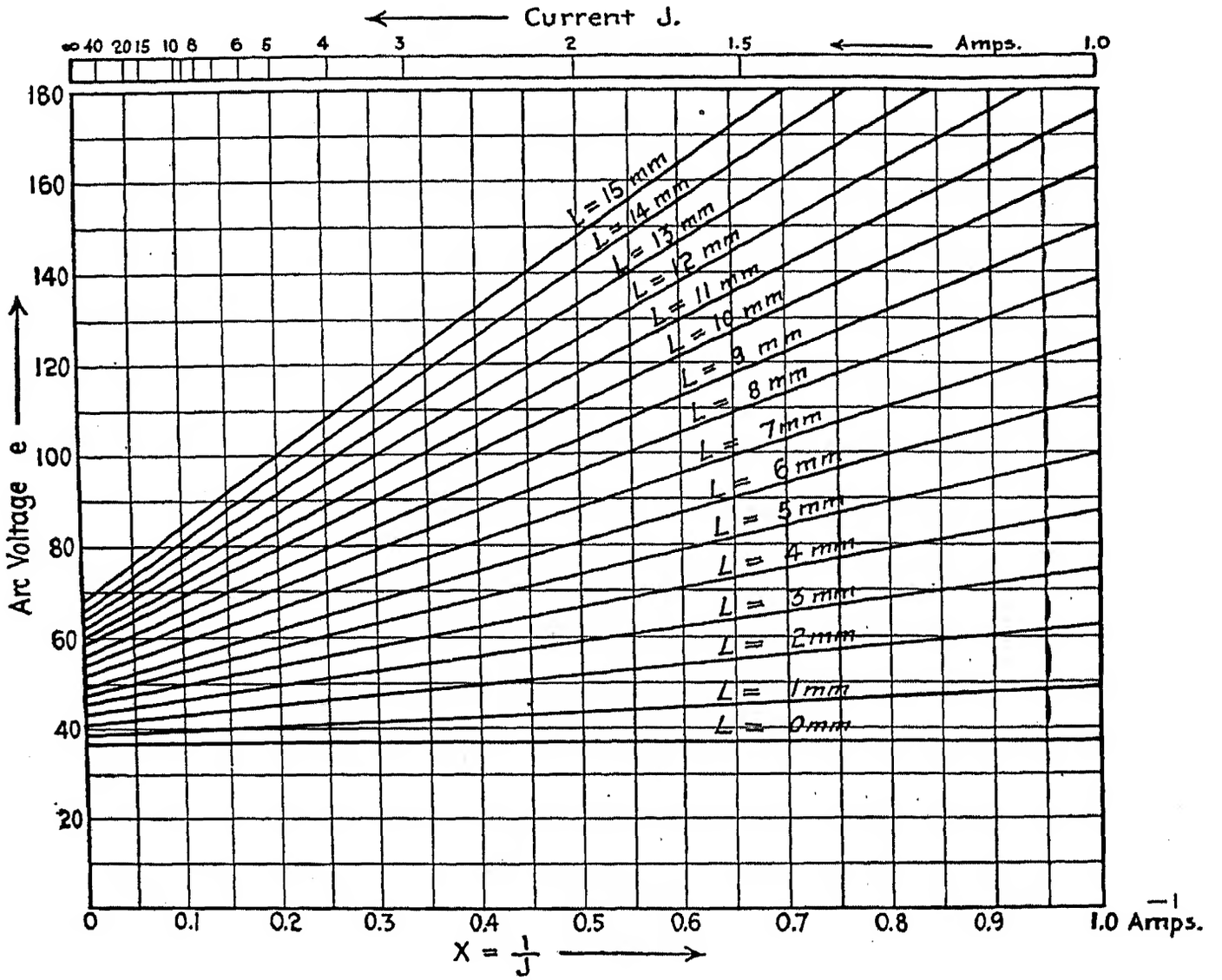


FIG. 25.

this have been used as abscissas, not the current J, but its reciprocal value $X = \frac{1}{J}$, with e values as ordinates.

We then obtain, instead of the system of hyperbolas, which have to be plotted point by point, a number of straight lines corresponding to different arc lengths from which related values of e and J can be found.

It should be mentioned that, lately, J. Stark has ap-

plied to glow discharges, and Koch to spark discharges, the equation of the arc characteristic, with good results. Thus, seemingly, a greater measure of validity should be given to this equation than would be due to it as a mere empirical interpolation formula.

For spark discharges of not too great length, according to Koch's observations,

$$e = m + \frac{C}{J} \text{ (volts)},$$

$$m = 300 + 86.4\,L \text{ (volts)},$$

$$C = 0.600\,L \text{ (watts)}$$

The numerical constants, naturally, are dependent on the electrode material and signify, respectively, the anodic voltage drop and the conductivity of the gases in the discharge path.

If, with current (J) kept constant, one measures the values of arc voltage (e) corresponding to different arc lengths (L), it will be found, as shown in Fig. 26, that with increasing arc length the arc potential e increases relatively slowly for high current values while for low currents the increase is very rapid. The tangents of the angles ϵ between the straight-line ampere curves and the abscissa can be directly calculated by differentiation of the equation for the characteristic curve; thus, according to equation (9) (page 77),

$$\tan \epsilon = \frac{de}{dL} = \alpha + \frac{\delta}{J}.$$

The locus for voltage drop de, referred to the length element dL, thus is a hyperbola which tends, with increase of current J, towards a minimum value α.

Of course, it is not permissible to draw any conclusions

whatever from the gradient of (e, L) curves belonging to two kinds of arc of different current strength, J_1 and J_2, without taking into consideration the complete characteristics.*

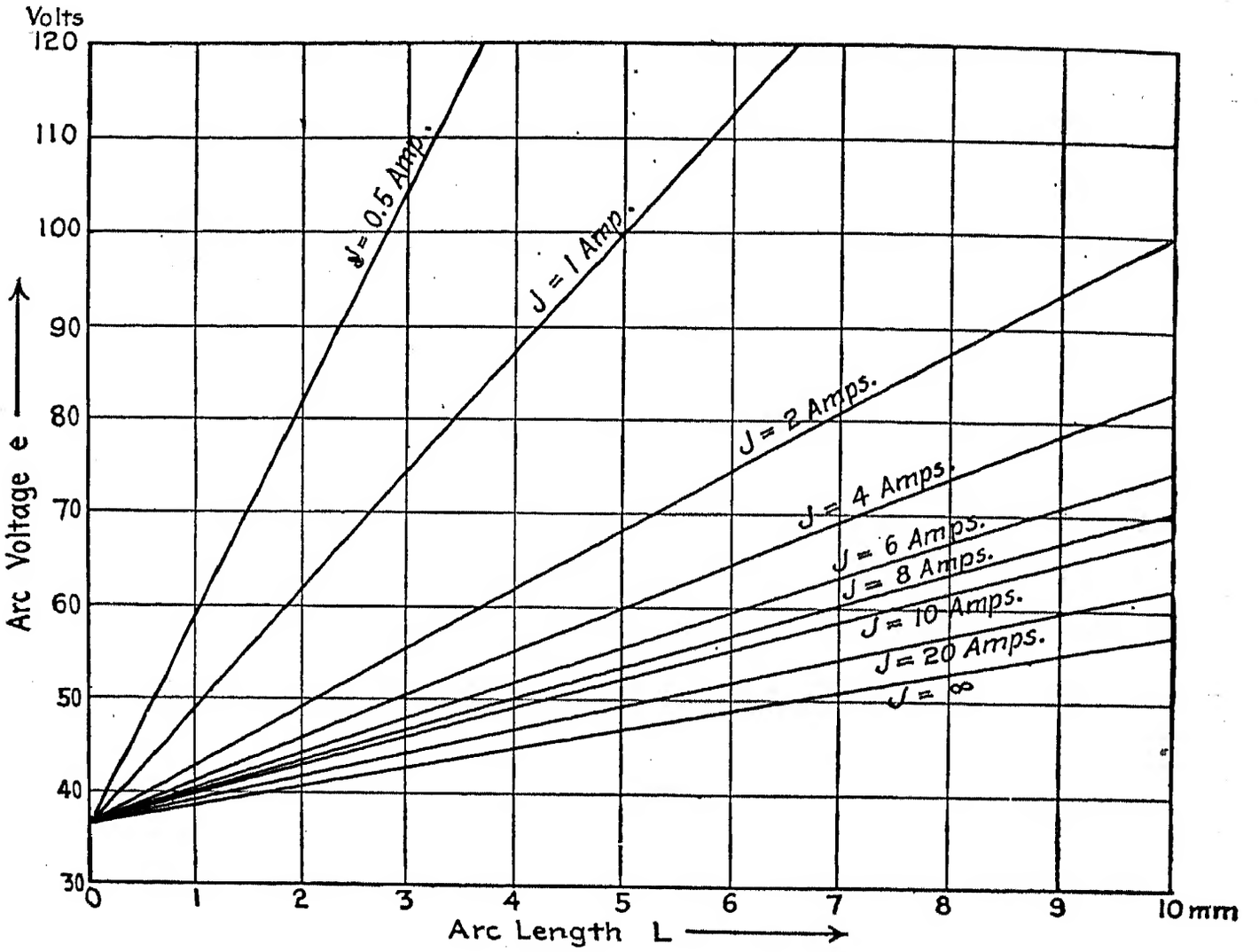


FIG. 26.

§ 20. Practical Derivation of Characteristics.

Although for practical work one prefers — generally with good reason — graphical methods to algebraic methods, the latter, nevertheless, are more suitable in complex cases — such as the present one — where it is desired to make an exhaustive comparison between different kinds of elec-

* Verh. d. Deutsch. Phys. Ges., 5, 276 (1903); ibid., 6, 139 (1904).

trodes, to find the relation of maximum efficiency to arc length and electrical conditions, the influence of gas pressure and nature of gas, and so on. A graphical representation in such a case would mean a complicated system of curves, an examination of which would only with difficulty, if at all, give a deeper insight into the effect of the individual variables.

It is for such problems that the use of Thompson-Ayrton's equation for $e_1 J$ hyperbolas is recommended, for which equations the author has proposed the name "characteristics."*

These equations give, moreover, a close, numerical idea of the conditions for stability (cf. § 23, page 92) and the series resistance required. They may be formulated without much trouble as follows.

An electric arc is produced and the length thereof, L, as well as the line voltage E, is kept constant. It is just as well to select for the test a length of arc of some especial interest and such as may have practical application in arc lamps.

The current is first adjusted, by means of the series resistance, to a definite value J and a reading taken of the arc voltage e. It should be remembered, especially in case of carbons containing admixture of conductors of the second class, that there is an appreciable ohmic voltage drop in the electrodes themselves.

A second, third and fourth, etc., current value is then similarly adjusted by means of the resistance and for each current after the lapse of a sufficient time (which eventually can be usefully employed for photometric test) the corresponding arc voltage e is taken.

In this manner one obtains a series of correlated e and J values all referring to the particular arc length chosen.

* Verh. d. Deutsch. Phys. Ges., 5, 276 (1903).

These data are sufficient for expressing the simplest form of characteristic (see page 71),

$$e = m + \frac{C}{J}, \tag{1}$$

and for finding the values of the constants C and m.

If it is desired to formulate an equation valid for all values of J and L, a number of similar series of observa-

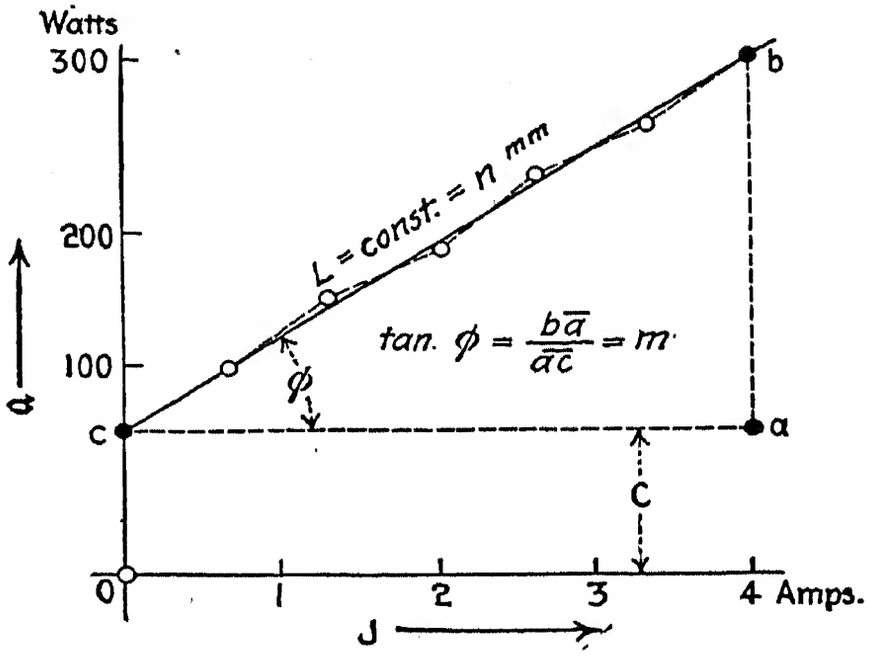


FIG. 27.

tions is made, for other arc-length values L_2, L_3, L_4, etc. These different sets of data give a series of correlated C and m values bearing to the arc length a linear relation which can be represented graphically as a straight line (see Fig. 23, page 75).

First Method. — If both sides of the equation (1) be multiplied by J one will recognize the values $eJ = \alpha$ as representing the total amounts of energy consumed in the arc. This secondary variable is a straight line, the equation of which is

$$eJ = \alpha = C + mJ.$$

Hereby the problem of plotting a hyperbola is at once transformed into the much easier one of determining the constants of a straight line.

For this purpose a plot is made, to a suitable scale, on millimeter cross-section paper, using as ordinates the α values (watts) obtained by multiplication of the observed e values, and as abscissas the corresponding J values (amperes) (see Fig. 27).

Through the series of points so determined a "best representative line," $\overline{cb}$, is then drawn so as to distribute the points as nearly as possible equally on the two sides.*

The intercept of this line with the ordinate axis ($J = 0$) is the constant C in watts. The constant m is given by the quotient

$$\tan \phi = \frac{\text{distance } \overline{ba}}{\text{distance } \overline{ac}} = m.$$

Second Method. — The problem becomes still more comprehensive if, side by side with the observed J values, one writes down in the tabulation of test data the reciprocal values $\frac{1}{J} = X$ and plots these values as abscissas against corresponding voltages e as ordinates (Fig. 28).

The intercept of the line $\overline{mh}$ with the e axis is the constant m; the trigonometric tangent

$$\tan \epsilon = \frac{\overline{hf}}{\overline{fm}} = C$$

is the numerical value of the constant C.

* A convenient way for doing this is to draw a thin, straight line on a piece of tracing cloth and place the latter over the curve sheet (Fig. 27) adjusting its position so that the observed values will be located as uniformly as possible around the line. With a pin two points on the latter (for instance, c and b) are marked through the tracing cloth on the curve sheet and through these marks is drawn a straight line, "the best representative line."

If the complete equation of the characteristic is desired, this procedure is repeated for several values of arc length L, plotting the resulting C values (or m values) as ordinates and corresponding L values as abscissas. Thus the values of the constants g and α or γ and δ may be obtained as before (§ 18; also Table 15) from the equations of the straight lines,

$$m = g + \alpha L,$$
$$C = \gamma + \delta L.$$

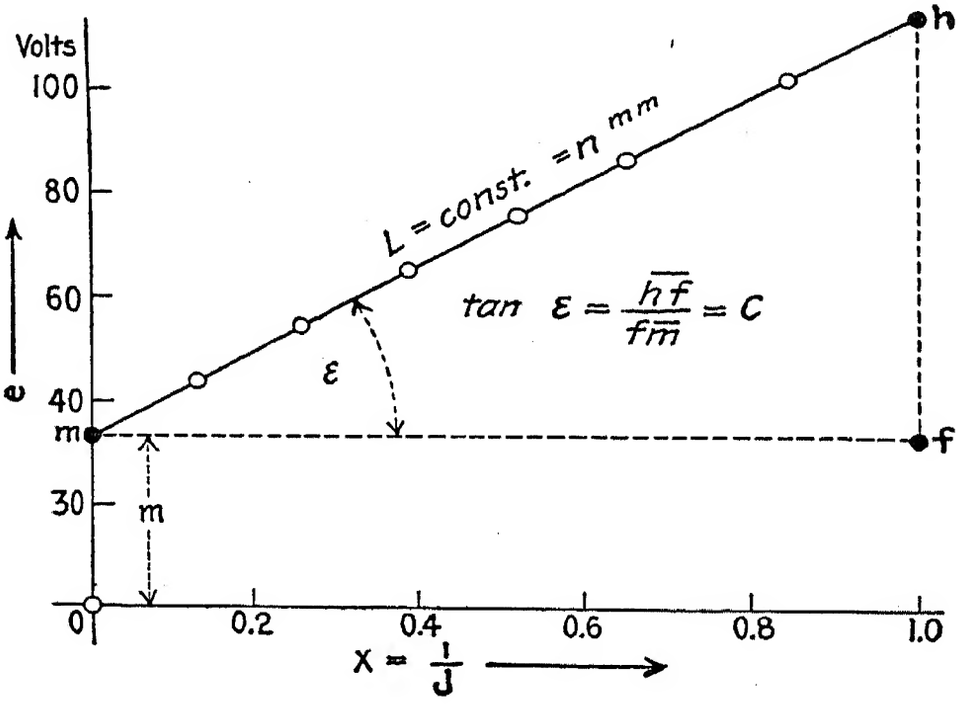


FIG. 28.

§ 21. Characteristic of the Alternating-current Arc.

The experiments which have been made bearing on the characteristics of the alternating-current arc are far from satisfactory. So much is clear, however, that in this case also we may expect a system of hyperbolas, if for e and J we use the effective mean values of voltage and current. The general constants of these hyperbolic equations have not been determined, however.

On the basis of experiments made by Heubach * we

* E.T.Z., 13, 460 (1892).

may conclude, nevertheless, that for alternating currents, also, the power curves eJ can be represented by a system of straight lines, if eJ is plotted as a function of the arc length L (J = const.) as well as when it is plotted as a function of J, keeping the arc length L constant.

From Heubach's curves we get,

for $J = 4.4$. amps.,
$eJ = 89.1 + 9.05\,L$ watts;
for $J = 6.5$ amps.,
$eJ = 138.2 + 11.6\,L$ watts;
that is, for $J = 4.4$ amps.,

$$e = 20.3 + 9.05\frac{L}{J} \text{ volts};$$

and, further, for $J = 6.5$ amps.,

$$e = 21.3 + 11.6\frac{L}{J} \text{ volts.}$$

Making $J = \infty$, we then find the minimum potential m to be about 20.3 to 21.3 volts; thus, in absolute amount smaller than the minimum potential for direct-current arcs.

For $J = \infty$ Hertha Ayrton's formulas referring to direct-current arcs give as the ratio between anode drop e_1 and cathode drop e_2,

$$\left(\frac{e_1}{e_2}\right)_\infty = \frac{31.28}{7.6} = 4.11.$$

In reality the cathodic drop e_2 probably is considerably smaller. (cf. page 72.)

The sum of the voltage drops of both electrodes is, according to Hertha Ayrton,

$$e_1 + e_2 = 38.88 \text{ volts},$$

while Heubach's experiments with alternating-current arcs point to a value $e_1 + e_2$, approximately 20.8 effective volts,

of which the greater portion consists of the potential drop e_1 at the anode.

The energy consumption of alternating-current arcs, 2 mm. in length at 6 amperes, is, for the following different carbon combinations:

	Watts.
Two solid carbons	266
Upper carbon cored, lower solid	168
Upper carbon solid, lower cored	159
Two cored carbons	142

Cored carbons thus consume only about 53 per cent of the energy taken by solid carbons. This is due to the greater conductivity of the arc flame caused by the metallic vapors supplied to it from the core.

Furthermore, the anodic minimum potential e_1 is greatly reduced by the presence in the electrodes of metallic salts, since the latter, plainly, will require a much lower temperature for vaporization than carbon and in addition have a low latent heat of vaporization.

If several arcs are burning in series and if Σe is the algebraic sum of their arc voltages, the current J which passes through each arc, will be determined by the value R of the resistances in the metallic circuit, i.e. (Fig. 21),

$$J = \frac{E - \Sigma e}{R}.$$

Obviously in the case of arcs produced by alternating current of the frequency ν, the value of R is not the ohmic resistance R_0 but the apparent resistance,

$$R = \sqrt{R_0^2 + (2\pi\nu S)^2},$$

of the choke coil, generally — and with advantage — used in the circuit as a substitute for the steadying resistance.* (S = self-induction in henrys.)

* See J. Zeidler's "Die elektrischen Bogenlampen."

§ 22. Influence of the Surrounding Gases on Current and Voltage of the Arc.

The nature of the gases in which the arc is burning will affect its volt-ampere characteristic to a considerable extent.

This much is definitely known that, with current and arc length the same in both cases, to maintain an arc in hydrogen requires the highest, and in nitrogen the lowest, voltage.

Simon gives the following data referring to direct-current carbon arcs (Fig. 29 and Table 16):

TABLE 16. THE CONSTANTS IN THE EQUATION

$$e = m + \frac{C}{J}.$$

Carbon arc.	Length of arc, L=4 mm.		Length of arc, L=8 mm.	
	m (volts).	C (watts).	m (volts).	C (watts).
In hydrogen	60	180	35	455
In water vapor with exclusion of air	70	110	35	300
In nitrogen	62	30	105	35
In air	49.5	31.5	60	49

Since the carbons do not remain chemically indifferent these data possess only comparative value.

Grau and Russ * have investigated high-voltage alternating-current arcs between platinum electrodes, the use of which arcs for oxidation of nitrogen has lately come to the forefront of technical interest. One of the electrodes was kept cool artificially. An arc 50 mm. in length was experimented with.

* Zeitschr. f. Elektroch., 13, 345 (1907).

The results obtained by Grau and Russ have been plotted in Fig. 30. The arc voltage e has been used for ordinates and the reciprocal value $\left(X = \frac{1}{J}\right)$ of the current as abscissas (see § 20). It will be noted that the gradients of the curves (that is, the constant C) for hydrogen,

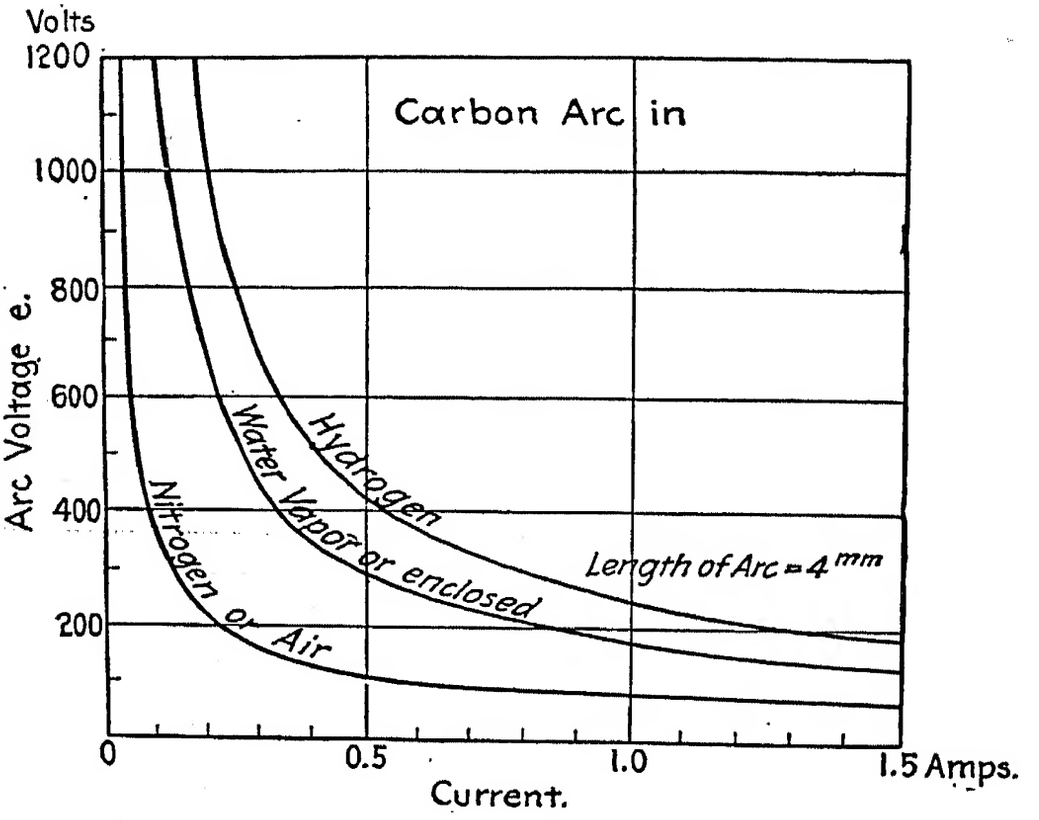


FIG. 29.

oxygen, sulphur dioxide and nitrogen do not differ much from one another. (See Table 17.)

On the other hand, the minimum voltage in the characteristic $e = m + \frac{C}{J}$ is influenced in a very pronounced degree by the nature of the gases. While with the tests as carried out the minimum voltage for nitrogen was found to be $m = 790$ volts, a value over five times as great was established for hydrogen (4100 volts). It is noteworthy that both the minimum voltage and the constant C in the characteristic for pure oxygen (Table 17) are considerably modified by the admixture of small

quantities of nitrogen. (cf. § 9, pages 26 and following.) Obviously this is due to the relatively good conductivity of the nitrous oxide formed.

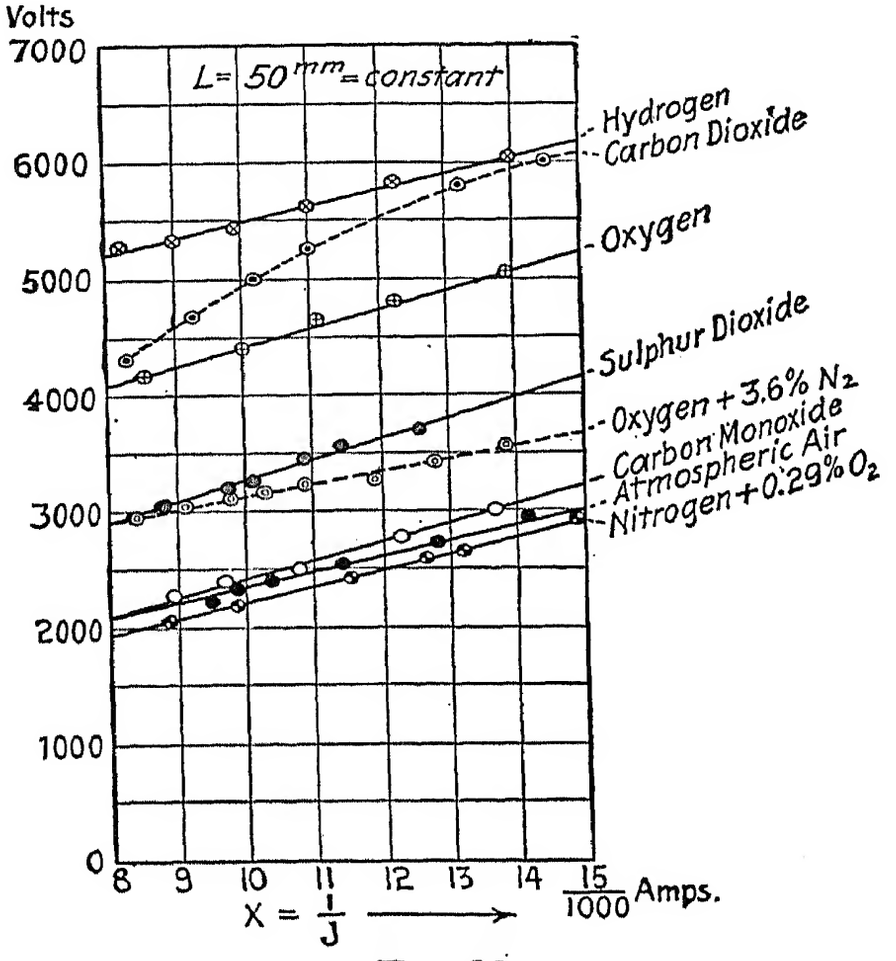


FIG. 30.

By comparison of Tables 15 and 17 we see that for the maintenance of alternating-current arcs very much higher voltages are required than for direct-current arcs.

The characteristic for carbon dioxide (Fig. 30) evidently is distorted, due to the dissociation

$$2\,CO_2 \rightleftarrows 2\,CO + O_2$$

which takes place and complicates the electrical conditions.

Anomalies are manifested, also, in the characteristics of Table 17 for currents under 0.6 amp., which irregularities, however, can be attributed to peculiarities of the test arrangements. (cf. § 9, pages 26 and following.)

TABLE 17. INFLUENCE OF DIFFERENT GASES ON THE CHARACTERISTIC OF THE ALTERNATING-CURRENT ARC.

Length of arc: $L = 50$ mm. = constant.
Electrodes: platinum; one electrode artificially cooled.

Gas.	$e = m + \frac{C}{J}$.		Appearance of arc.
	m (volts).	C (watts).	
Hydrogen (98.4 % H_2).....	4100	137	Thin poorly luminous band of bright blue color.
Carbon dioxide, pure.....	....	....	Strongly luminous blue, flickering flame.
Oxygen, pure.....	2720	168	Bright blue flame.
Sulphur dioxide (99.2 % SO_2)	1440	184	Brightly luminous, broad flickering flame of a color similar to that of the mercury arc.
Oxygen+3.6 % N_2.....	2010	110.5	Bluish luminous band bordered by a reddish-brown halo of nitrous oxide.
Carbon monoxide (88.4 % CO+9.4 % N_2+2.2 % O_2)	820	159.5	Rose colored band surrounded by a thicker greenish-blue envelope.
Nitrogen (0.2 % O_2).....	790	145.5	Purple colored band; feebly luminous edge of greenish tint.

§ 23. Conditions Necessary for a Steady Arc.

Although the electrical quantities involved in every form of arc discharge are continually fluctuating in magnitude within certain limits, as will be seen by examination of the characteristic curves (Fig. 22) there exist for all electrical discharges through gases certain critical current values at which the physical form of the discharge abruptly changes. (For instance, rupturing of the arc, change from glow discharge to arc discharge, sudden starting of an arc discharge when with a finite value of J the minimum potential has been reached, etc.)

Kaufmann* and, later, Granqvist† have shown that any kind of discharge is independently stable, and unsteadiness impossible, only when in the eJ characteristic the arc voltage e increases simultaneously with the current J.

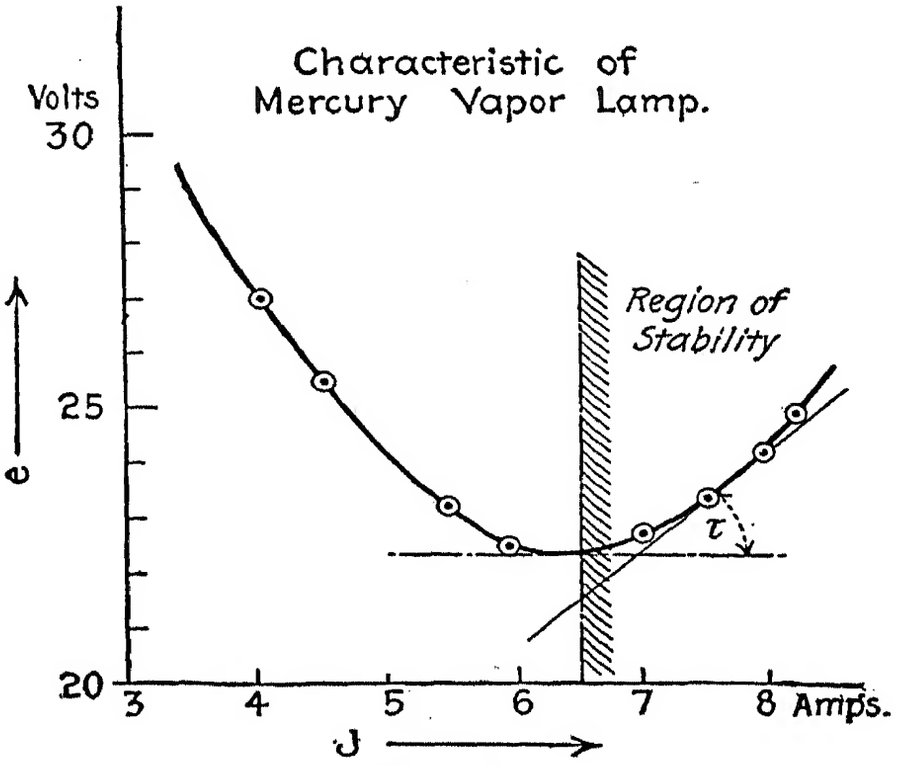


FIG. 31.

A glance at the characteristic hyperbolas in Fig. 22 (see page 73 and following) will show that this condition is not satisfied in the case of most kinds of electric arcs, and that these, therefore, do not constitute independently stable forms of electric discharge.

As an example of a stable arc discharge may be mentioned the mercury vapor lamp. This consists of a glass vessel exhausted to higher or lesser degree. In this an arc is formed between a cathode of mercury which is volatilized and a passive, metallic anode.

This type of arc has a very peculiar characteristic (see Fig. 31).

* W. Kaufmann, "Elektrodynamische Eigentümlichkeiten leitender Gase"; Ann. d. Phys. IV, 2, p. 158 (1900); Göttinger Nachrichten, 1899, p. 243.

† Vetenskapssocietén, Upsala (Sweden), 1903.

Up to a certain current value (in this case about 6.5 amps.), which depends on the geometrical shape of the glass vessel and on its external temperature, the arc voltage decreases with increasing current J, i.e., the differential coefficient $\frac{de}{dJ} = \tan \tau$ is negative. At 6.5 amperes (in the particular example shown in Fig. 31) it reaches zero value; in other words, the characteristic passes through a minimum. If the current be increased further $\frac{de}{dJ} = \tan \tau$ becomes positive. In this region of the curve, thus, the arc of the mercury vapor lamp is stable, while for currents below the critical value (in this case 6.5 amps.) it is like the carbon arc in not possessing independent stability and, therefore, requiring a steadying resistance R.

Kaufmann has shown that any form of discharge is stable when, and only when,

$$R + \frac{de}{dJ} > 0. \tag{1}$$

In this formula R is the total ohmic or apparent resistance of the metallic circuit including the internal resistance of the source of the electric current.

For a discussion of the subject of stability it is expedient to adopt a quantity $\mathfrak{S}$ so defined that it can serve as a measure for the steadiness of the arc. Thus the stability $\mathfrak{S}$ is a quantity which increases with increasing steadiness of the electrical discharge, becomes zero when the arc is extinguished and assumes a negative value when conditions are such as to make the maintenance of this kind of discharge impossible.

We may write, then,

$$\mathfrak{S} = R + \frac{de}{dJ}. \tag{2}$$

The differential coefficient $+\frac{de}{dJ}$ may be obtained graphically from the characteristic (Fig. 31) as the trigonometric tangent ($\tan \tau$) of any point (e, J) on the curve. $\frac{de}{dJ}$ will have negative sign as long as the voltage is decreasing and will become positive only when the voltage and current increase simultaneously.

A clearer and quite general formula for the conditions governing stability of the arc may be derived from the characteristic equations, which, thus, are of direct practical value for judging the conditions for existence of static discharges through gases.

The Ayrton equation (equation (5), page 72),

$$e = g + \alpha L' + \frac{\gamma + \delta L'}{J},$$

gives, directly, by differentiation,

$$\frac{de}{dJ} = -\frac{\gamma + \delta L'}{J^2}, \tag{3}$$

where L' is the length of arc according to the customary, objectionable definition. (cf. § 19, pages 70 and following; see also Fig. 24, page 76.)

If, instead of L', we use the true length L (see page 76) of the current-carrying gaseous path as indicated on Fig. 24, that is, if in equation (3)

$$L' = L - \frac{\gamma}{\delta}, \tag{4}$$

we may write

$$\frac{de}{dJ} = -\frac{\gamma + \delta\left(L - \frac{\gamma}{\delta}\right)}{J^2}, \tag{5}$$

or

$$\frac{de}{dJ} = -\frac{\gamma + \delta L - \gamma}{J^2} = -\frac{\delta L}{J^2}.$$

According to Hertha Ayrton the constant $\gamma = 11.66$ means a potential drop which is independent of arc length and which occurs at the starting points of the arc on the electrode tips.

It will be noted that in the modified form of the characteristic

$$e = m_0 + \alpha L + \frac{\delta L}{J},$$

γ is eliminated by using, instead of the apparent arc length L', the true length, which is the apparent length augmented by the depth of the crater, i.e., $L = L' + h$.

Thus we obtain, from Hertha Ayrton's equation, the stability

$$\mathfrak{S} = R - \frac{\gamma + \delta L'}{J^2}, \tag{6}$$

or, from the modified characteristic,

$$\mathfrak{S} = R - \frac{\delta L}{J^2}. \tag{7}$$

It is known that the conditions for stability of an electric arc are completely determined by the material constant δ. (cf. Table 15, page 79.)

As shown in Fig. 32, the value of δ decreases conspicuously as the specific heat (c) of the electrode material becomes higher (cf. § 12, pages 39 and following). As a first approximation

$$\delta = 23 \times 4\,(1 - 2.7\,c).$$

As we shall see later, the quantities $\delta L = \delta\,(L' + h) = \gamma + \delta L'$ in equations (6) and (7) represent the least energy J^2R, which under any circumstances must be absorbed in the external resistances (R) of the circuit for an arc to be capable of existing at all.

Any arc, thus, according to equation (7), will be extinguished if

$$\mathcal{S} = R - \frac{\delta L}{J^2} \leqq 0,$$

or, in other words, will become negative.

The corresponding critical values at which the arc will be extinguished are determined by the following expressions:

Maximum arc length,

$$L_{\max} = \frac{J^2 R}{\delta} \text{ millimeters.} \tag{8}$$

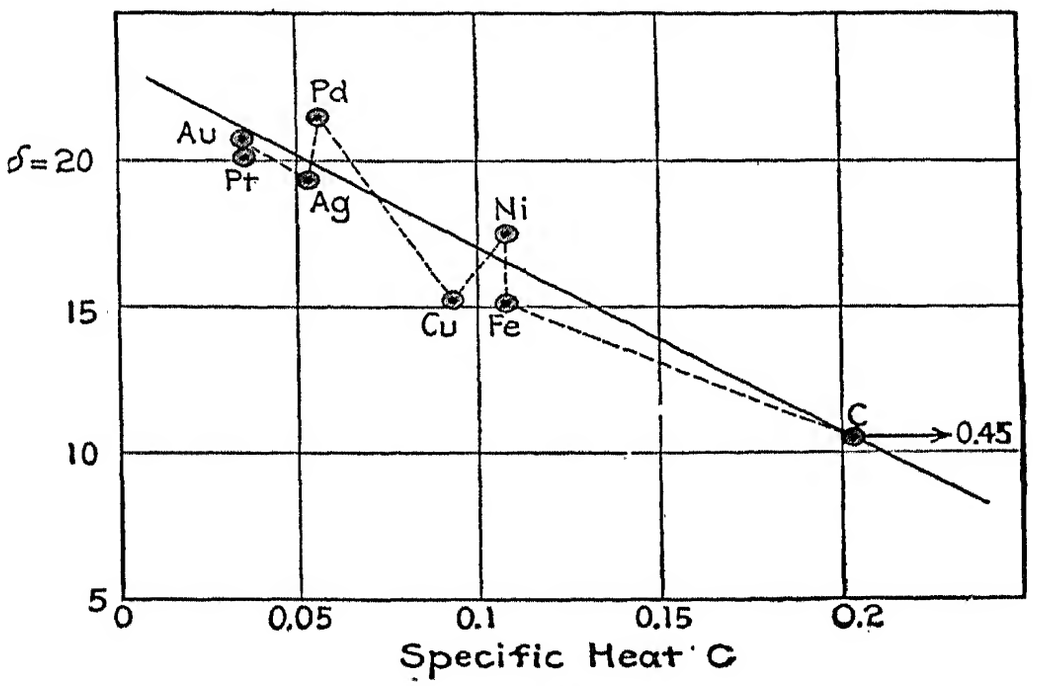


FIG. 32.

Minimum current,

$$J_{\min} = \pm \sqrt{\frac{\delta L}{R}} \text{ amperes.} \tag{9}$$

Critical value of steadying resistance,

$$R_{\text{crit.}} = \frac{\delta L}{J^2} \text{ ohms.} \tag{10}$$

Minimum energy to be dissipated in external resistance,

$$J^2 R = \delta L \text{ watts.} \tag{11}$$

From equation (11) we see that δL is the least amount of electrical energy which must be expended in an arc of the length L in order that it shall not become extinguished.

It is to be noted, in connection with equations (6) to (11) above that, obviously, Ohm's law applies fully to the external portions of the circuit.

Thus

$$J = \frac{E - ne}{R} = \frac{U}{R}, \tag{11a}$$

where $U = E - ne$ is the total voltage left over for the steadying resistance of n arcs connected in series (see Fig. 21). Evidently, therefore, we can write equation (11) also,

$$J^2R = UJ = \frac{U^2}{R}. \tag{11b}$$

In general practice the size and current of an arc lamp are determined in advance by the requirements for illumination and by the operating expense permissible.

If the volt-ampere characteristic of the arc has been determined and thereby also the material constant δ for the particular variety of electrodes (grade of carbon) which is to be used, equation (10) will give, directly, the value of the series resistance, and equation (8) the value of maximum arc length L, at which the arc will become extinguished.

If in equation (7) we substitute for R

$$R = \frac{E - ne}{J} = \frac{U}{J},$$

we can write for the stability

$$\mathfrak{S} = \frac{U}{J} - \frac{\delta L}{J^2}. \tag{12}$$

Differentiation with respect to J gives

$$\frac{d\mathfrak{S}}{dJ} = -\frac{U}{J^2} + \frac{2\,\delta L}{J^3}. \tag{13}$$

It appears from this that the stability of an arc of any given length reaches a maximum for finite values, shown in Fig. 33, for an overvoltage $U = 15$ volts and an arc length $L = L' + h = 3$ millimeters, namely when

$$\frac{d\mathfrak{S}}{dJ} = 0 \quad \text{and} \quad 2\,\delta L - UJ = 0.$$

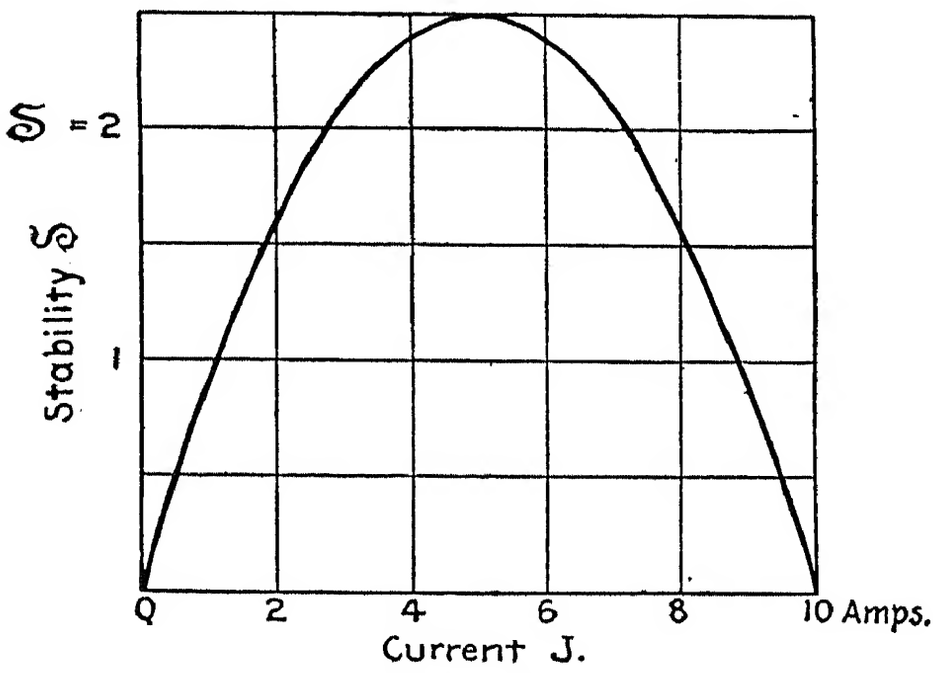


FIG. 33.

There obtains, consequently, an optimum for stability of the discharge when

$$L = L_{\text{opt.}} = \frac{UJ}{2\,\delta} = \frac{J^2R}{2\,\delta}. \tag{14}$$

If we compare this with equation (8) we find that the greatest possible stability obtains for an arc length,

$$L_{\text{opt.}} = 0.5\,L_{\text{max.}}$$

The maximum arc lengths L, corresponding to several values of critical overvoltage $U = E - e$, are shown, graphically, in Fig. 34. The value $\delta = 10.54$, as ob-

tained by Hertha Ayrton for solid carbons, has been used as a basis for these curves. The values for L are those of the true arc length as already defined (see Fig. 24, page 76).

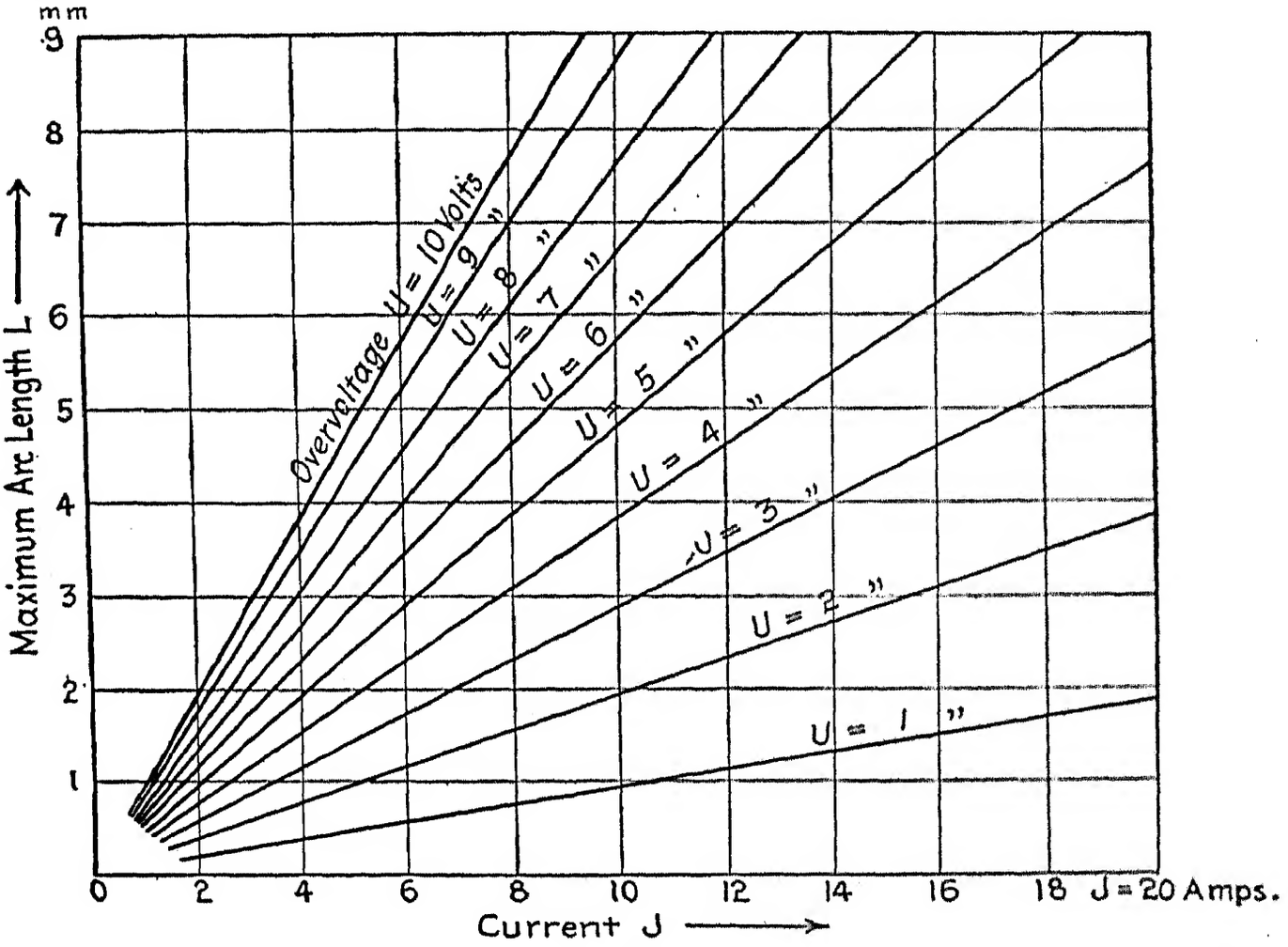


FIG. 34.

The relation of the critical series resistance to the arc length L and the overvoltage U is illustrated by the curves in Fig. 35.

As an experimental, even though only qualitative, check of the above relations may serve the data by Granqvist in Table 18, in which it is to be regretted that the critical arc voltages, $e_{crit.}$ and corresponding overvoltages, $U = E - e_{crit.}$, have not been included. From these data we see (column 4) that with constant supply voltage the quotient $\frac{L'_{max}}{J}$ also is approximately of con-

stant value, which is in accord with what has been said above.

If the data (Table 18) for L'_{max} be plotted as a function of J, it will be found that L'_{max} bears a linear relation to J.

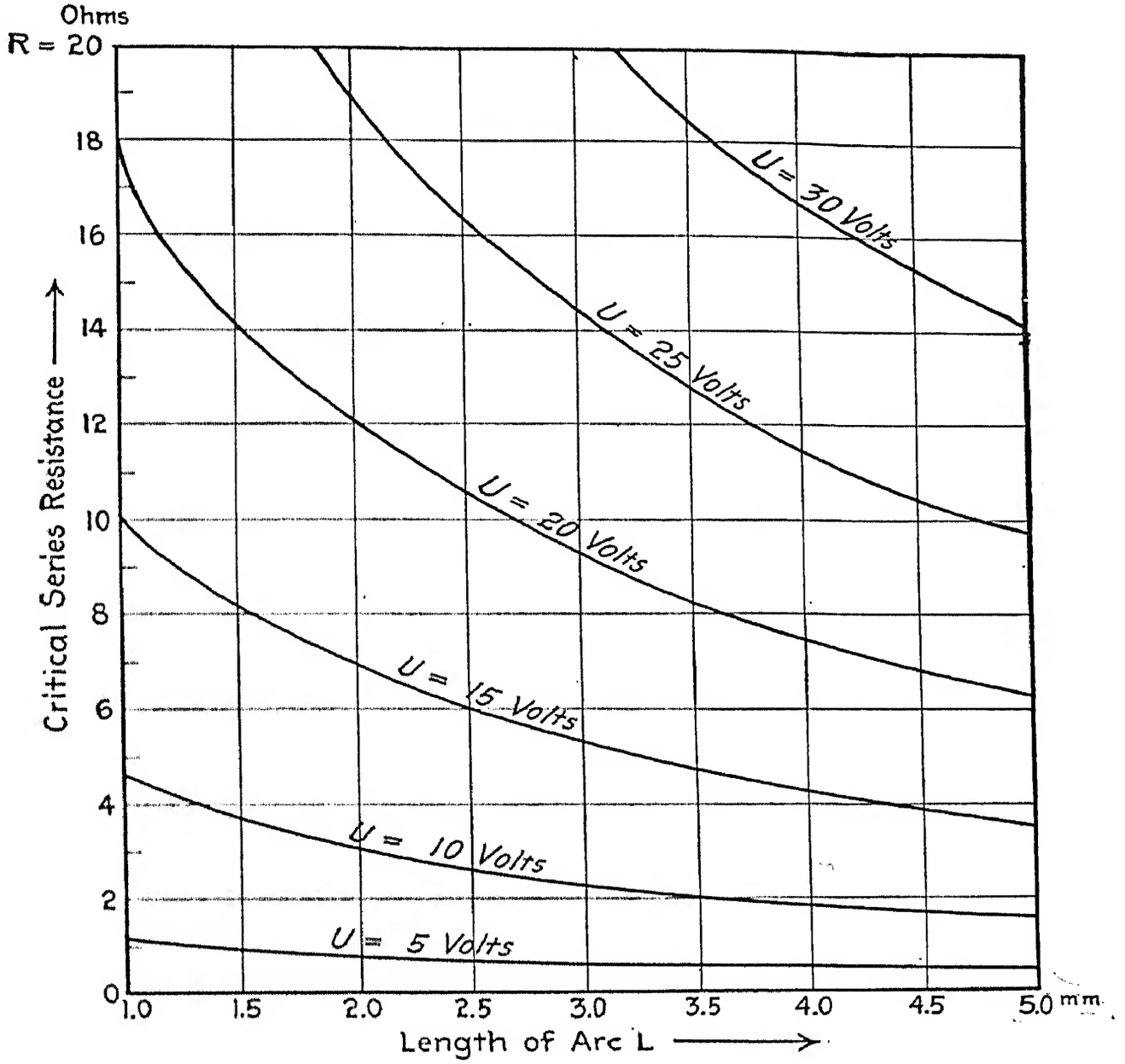


FIG. 35.

Evidently the straight line curves representing this relation must pass through the origin of the coördinate system; and we cannot go far wrong by assuming that any irregularities in this respect, which are manifest also

TABLE 18. RELATION OF MAXIMUM ARC LENGTH (L'_{max}) TO SUPPLY VOLTAGE (E) AND CURRENT (J).

(GRANQVIST.)

Supply voltage E (observed value) volts.	Maximum arc length L'_{max} (observed value) mm.	Current J (observed value) amps.	$\frac{L'_{max}}{J}$.	Graphically $\frac{\Delta L'}{\Delta J}$.
110 ($U=67.4$)	9.6	3.0	3.20	(Approx.) 2.81
	12.0	4.0	3.00	
	14.9	5.0	2.98	
	18.0	6.0	3.00	
		Mean:	3.045	
99 ($U=56.4$)	6.7	3.0	2.23	(Approx.) 2.43
	7.2	3.25	2.22	
	7.7	3.5	2.20	
	9.2	4.0	2.30	
	12.6	5.0	(2.52)	
		Mean:	2.24	
84 ($U=41.4$)	2.4	2.0	1.20	(Approx.) 1.62
	3.8	3.1	1.226	
	4.3	3.45	1.248	
	4.7	3.7	1.27	
	5.16	4.0	1.29	
	5.76	4.5	1.28	
	6.7	4.9	1.368	
		Mean:	1.27	
54 ($U=11.4$)	1.3	2.6	0.50	(Approx.) 0.462
	1.8	3.25	0.555	
	1.92	4.0	0.48	
	2.16	4.9	0.441	
		Mean:	0.494	

in Granqvist's data, are due to the difficulty of determining the actual length of the conducting vapor stream of the arc.*

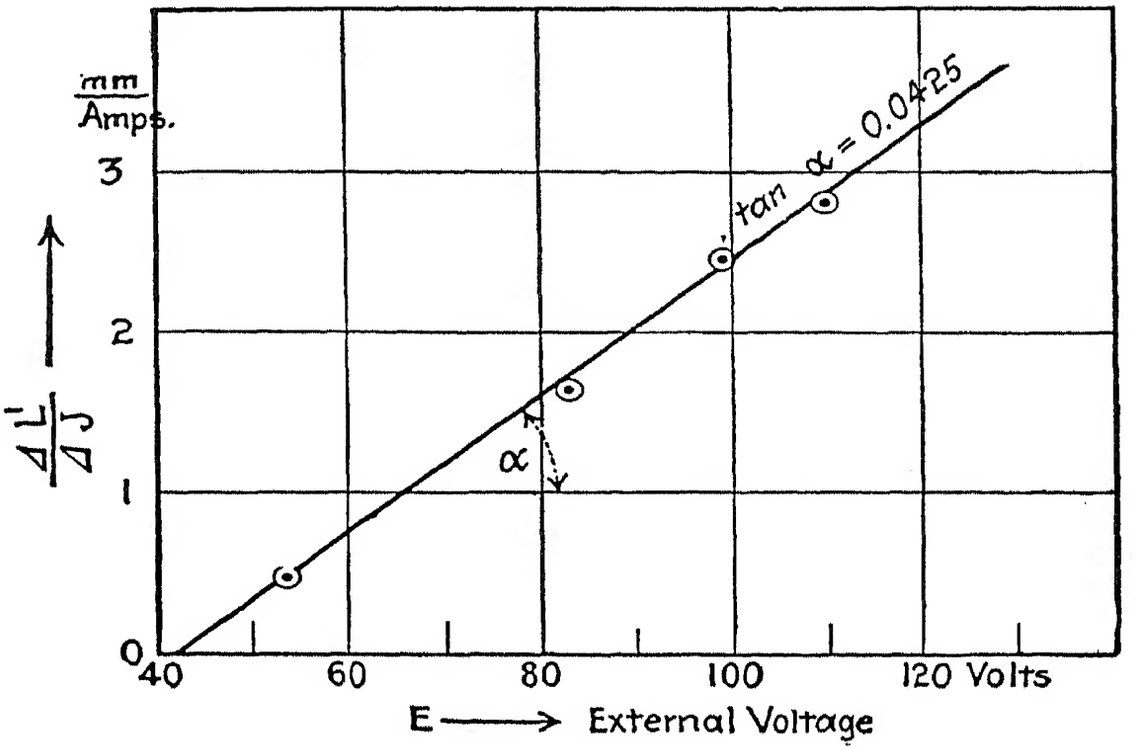


FIG. 36.

If we make allowance for these — satisfactorily explained — irregularities, a graphical determination of the slope of the straight lines $\frac{\Delta L'_{\max}}{\Delta J_{\max}}$ for different supply voltages gives the values found in column 5 of Table 18. The relation of these values to the voltage supplied is shown in Fig. 36.

According to equation (8) (page 97) or (11b) (page 98)

$$L_{\max} = \frac{J^2 R}{\delta} = \frac{UJ}{\delta}.$$

* Compare with this what has been set forth in § 19 and following. The difficulty of establishing the active arc length L is still more pronounced if the current filaments of the arc flame be distorted by air currents or magnetic effects. In such cases evidently the true arc length can be considerably greater than the direct distance L' from one electrode tip to the other.

Thus it follows that

$$\frac{\Delta L'_{\max}}{\Delta J} = \frac{U}{\delta} = \frac{E - e}{\delta} = \text{constant.}$$

This is verified by Fig. 36. According to the latter,

$$\frac{\Delta L_{\max}}{\Delta J} = 0 \quad \text{for} \quad U = E - e = 42.5 \text{ volts.}$$

The slope ($\tan \alpha$) of the curve in Fig. 36 represents the value $\frac{1}{\delta}$, where $\delta = 23.5$ in this particular case is referred to the apparent arc length L', and thus approximates Hertha Ayrton's value $\gamma + \delta = 22.2$.

§ 24. Phenomena at Starting and Extinguishing of the Arc.

Direct Starting, by Contact between Electrodes. Indirect Starting, by Auxiliary Arcs or Flames.

Hertha Ayrton's equation, against the principles of which, so far, no objections have been raised, led us in the foregoing to the conclusion that the stability $\mathfrak{S}$ of any form of discharge is insured only as long as

$$\mathfrak{S} = R + \frac{de}{dJ} \geqq 0, \tag{1}$$

$$\mathfrak{S} = R - \frac{C}{J^2} \geqq 0, \tag{2}$$

$$\mathfrak{S} = R - \frac{\delta L}{J^2} \geqq 0, \tag{3}$$

i.e., as long as $\mathfrak{S}$ has a finite, positive value.

If we continue to consider the Ayrton equation as a satisfactory expression for the physical facts involved, we may deduce the following:

Since in equation (2)

$$\delta L = C = (e - m)\, J,$$

it follows, as a condition for stability, that

$$\mathfrak{S} = R - \frac{e - m}{J} \geqq 0. \tag{4}$$

From equations (3) and (4) we learn that:

1. The stability of the discharge always increases with increase in current, since the minus quantity in equations (3) and (4) becomes smaller as the value of the current becomes larger.

2. The arc will possess true physical stability only when there exists in series with the arc a resistance R, whether this be located in the supply circuit or within the source of supply itself, which resistance has a critical value:

$$R' = \frac{c}{J^2} = \frac{\delta L}{J^2} = \frac{e - m}{J} \text{ ohms.}$$

On the other hand, it follows from equation (4) that an arc is possible only below a quite definite maximum voltage.

According to the Ayrton equation an arc of a certain length L will become extinguished when the arc voltage e exceeds the critical value $M = e'$,

$$M \cong JR + m. \tag{5a}$$

But we must not forget that in an arc circuit — whatever equation the characteristic may have — the following conditions imposed by the law of conservation of energy must always be satisfied:

$$\underset{eJ}{\text{Power in arc}} = \underset{EJ}{\text{Total power}} - \underset{J^2R.}{\text{Power in resistance}} \tag{5b}$$

Since in equation (5a) $JR = E - e$, and it follows that the maximum voltage $e' = M$,

$$M = E - M + m,$$

$$M = \frac{E + m}{2} \text{ volts.} \tag{6}$$

The adoption of H. Ayrton's data, consequently, leads to the conclusion that an arc can exist only as long as the arc voltage does not exceed a certain proportion, defined by equation (6), of the supply voltage E.

In accordance with the above an arc will go out when its voltage reaches or exceeds the value $\frac{E+m}{2}$. The Ayrton hyperbolas which it is customary to discuss up to $e = \infty$ thus lose all significance for arc voltages greater than $\frac{E+m}{2}$.

For a given voltage E of the generator or of the supply circuit the arc will lack stability, that is, it may rupture or change into some other form of discharge (glow discharge or the like) as soon as its voltage exceeds

$$e' = M = \frac{E + m_0 + \alpha L}{2},$$

where $m_0 = 36.59$ and $\frac{\alpha}{2} = 1.037$.

We see, then, that arc discharges are limited on the one side by Ayrton's minimum voltage $m' = m_0 + \alpha L$, and on the other by a critical maximum voltage M.

Furthermore, it follows from equations (4), (5) and (6) that, with a constant supply voltage E, an arc is physically possible only as long as the current is greater than a definite critical minimum value i, which — always assuming the validity of Ayrton's equations — is given by the equation,

$$i = \frac{M-m}{R} = \frac{E+m-2m}{2R} = \frac{E-m}{2R}. \qquad (7)$$

The limiting current i thus is greater the greater the available supply voltage. It becomes less as the value of $m = m_0 + \alpha L$ becomes smaller, i.e., with decrease in

arc length L, as well as with increase of the external resistance R in the circuit.

The following discussion will throw a light on the part played by the different factors in the starting or extinguishing of an arc.

Hertha Ayrton's hyperbolas are constructed (cf. § 20, pages 82 and following) by plotting the variations in current J corresponding to a series of step-by-step changes in the series resistance R, the supply voltage being kept constant.

If, in Ayrton's equation,

$$e = m + \frac{C}{J},$$

for the value of J be substituted

$$J = \frac{E - e}{R},$$

we obtain for the arc voltage e the quadratic equation

$$e^2 - e\,(E + m) + mE + CR = 0. \tag{7a}$$

Solving this equation for e,

$$e = \frac{E + m}{2} \pm \sqrt{\left(\frac{E - m}{2}\right)^2 - CR}, \tag{8}$$

where

$$m = m_0 + \alpha L',$$
$$C = \gamma + \delta L' = \delta L.$$

We have already shown in the foregoing (§ 19, page 70) that the following expressions give the numerical values of the constants m and C.

$$C = p\,(m - m_0) = \delta L,^* \tag{9}$$
$$m = m_0 + \alpha L, \tag{10}$$
$$C = \delta L = p\alpha L, \tag{11}$$

* From a casual remark (*l. c.*, p. 176) we may conclude that Hertha Ayrton used, for her investigation of the arc, a generator with a terminal voltage $E = 150$. The value of the term $pm_0 = 185.88$ thus agrees strikingly well with that of $E + m_0$.

where

$$p = 5.08,$$
$$m_0 = 36.59,$$
$$\alpha = 2.074,$$
$$\delta = 10.54.$$

According to equation (8) the arc voltage, thus, is exclusively determined by the arc length L and the electrical conditions in the circuit such as the voltage E and the resistance of the source of current, respectively, of the supply circuit.

At constant supply voltage E of the source, the arc voltage e will vary only when the quantity $CR = \delta RL$ is varied, consequently only when the external resistance R or the arc length L is changed.

We learn, further, from equation (8) that the arc voltage e becomes imaginary and an arc physically impossible when

$$CR = \delta LR \geqq \frac{(E - m)^2}{4},$$

or

$$R \geqq \frac{(E - m)^2}{4\,\delta L},$$

or

$$L \geqq \frac{(E - m)^2}{4\,\delta R}.$$

The curve in Fig. 37 shows how the arc voltage e will change if the quantity $CR = \delta LR$, i.e., the series resistance R or the arc length L be progressively varied. ($E = 160$; $m_0 = 40$.)

An examination of this curve will give an insight into the mechanism of the starting or extinguishing of the arc.

Contact Starting. — If the arc circuit contains a constant resistance R, the arc length, due to consumption of the

electrodes, will increase gradually, unless a regulating mechanism is provided, which will automatically feed them together to compensate for the consumption.

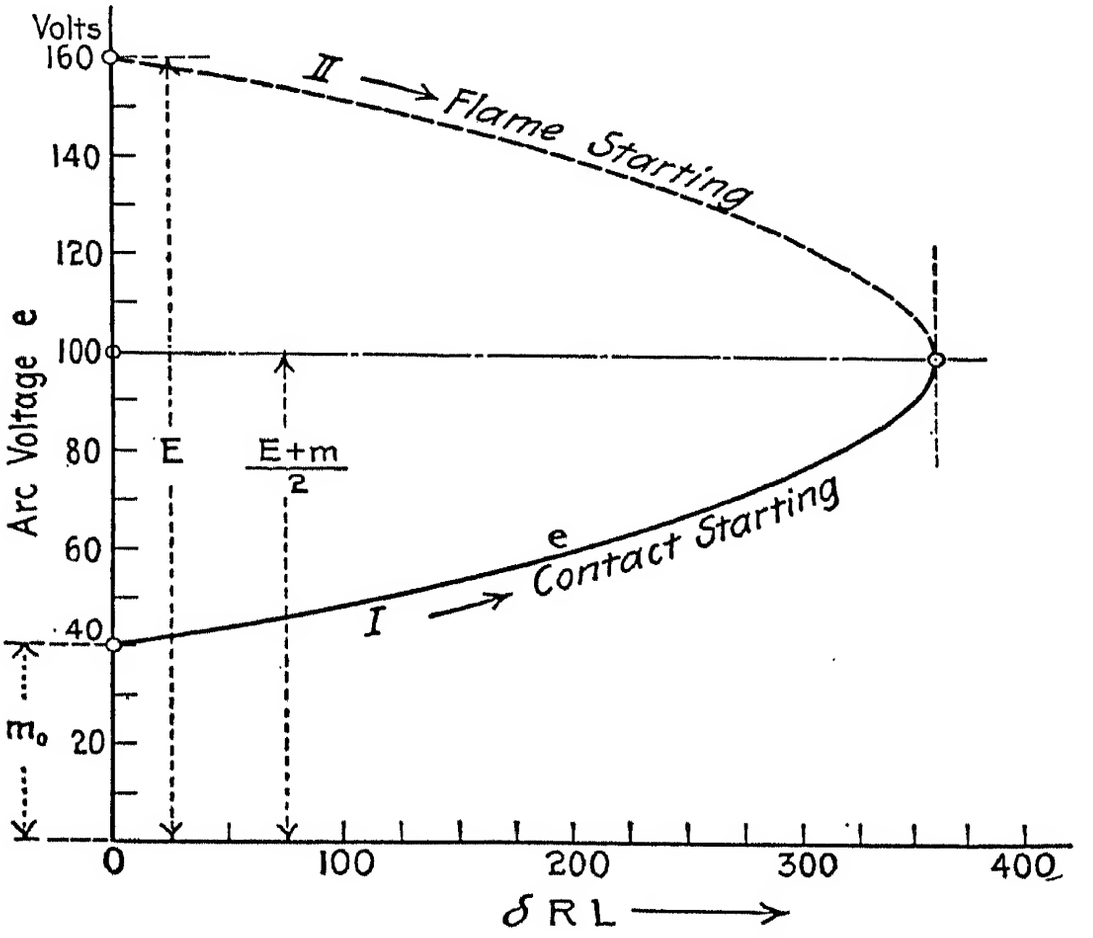


FIG. 37.

In consequence, the auxiliary variables $m = m_0 + \alpha L$ and $CR = \delta RL$ will assume progressively increasing values as a result of which the arc voltage e will go through a corresponding change as shown in Fig. 37.

The upper branch of the curve represents values of e greater than $\frac{E + m}{2}$, thus, such as will be obtained by putting a positive sign before the square root in equation (8).

As has been shown in the foregoing, these values of the arc voltage denote an unstable form of the discharge,

whereas the lower branch $\left(e < \frac{E + m}{2}\right)$ refers to the stable form in which an arc is capable of existing as such for a time.

From this it follows that in contact starting of an arc, the action sets in for arc length $L = 0$ with the potential $e = m_0$, which is the short-circuit voltage.

The arc voltage e rises steadily as the length of the arc, L, increases. Beginning at $e = m_0$ it reaches a turning point of the curve at $e = \frac{E + m}{2}$ and $L = L_{max}$. After that it enters the unstable range and rapidly approaches in value the total external voltage E, while the arc length at the same time diminishes from L_{max} to $L = 0$; in other words, the arc ruptures.

The statement that the physical form of the discharge is not stable when $e \cong \frac{E + m}{2}$ plainly must not be construed to the effect that in this range every form of electrical discharge is impossible.

On the contrary, other kinds of discharge, such as glow discharges, spark discharges, etc., are quite feasible.

For instance, when experimenting with oxide arcs at relatively low voltages ($220 > e > 120$ volts; $E = 220$ volts) the author observed sudden changes of the arc discharge into spark discharge. Under certain conditions a stream of crackling bluish sparks passed between the white-hot oxide electrode tips (magnesia, thoria, zircon-yttria, calcium oxide, etc.), sparks which under other circumstances — between cold or metallic electrodes — would have required many thousand volts to produce.*

In starting an arc by contact, as is the usual practice, the action takes place in the direction of arrow I (Fig. 37).

* Cf. also Ann. d. Phys., 11, 202 (1903).

The so-called minimum potential $e = m_0$ for $L = 0$ corresponds to conditions as they exist when the electrodes are together. For this short circuit, however, the current is not of infinite value as would follow from the Ayrton equation. On the contrary, the maximum current at short circuiting of the electrodes has the finite value

$$J = \frac{E}{R},$$

since R, the total resistance of the circuit, or eventually the internal resistance of the source of current supply, always possesses finite values.

Strictly speaking, therefore, the Ayrton minimum voltage m is conditioned by the external voltage E and the external resistance R and has only extrinsic connection with the inner workings of the arc itself.

Auxiliary Starting. — Quite different is the mechanism of starting an arc if, instead of bringing the electrodes into contact with each other, we employ some auxiliary means to start the arc. In principle this consists of ionizing (i.e., making conductive) the space between the electrodes, — more especially when the latter are made of metallic oxides.

This can be accomplished by heating the ends of the electrodes to incandescence through some auxiliary arrangement — eventually electrical. But a simpler way is to allow a flame to play on and around the electrode tips.

All flames are conductive in a marked degree, which can be still more heightened by the presence therein of vapors from the alkaline metals and rare earths.

As the author has shown * the characteristic equation is applicable also to electrolyte-arcs. For alternating-

* German Patents Nos. 117214; 137788 (1899); E. T. Z., **22**, pp. 155 (1901); Ann. d. Phys., **9**, 164 (1902).

current arcs between zirconia-yttria electrodes he found the minimum voltage to be $m = 31.4$ volts. The principal portion of this consists of the anode drop e_1, the cathode drop e_2 being inconsiderable. The constant δ, which proved to be dependent on melting point and vaporization temperature of the oxide mixture, was found to be about 30 for the more refractory varieties of electrodes, i.e., those made of oxide mixtures relatively difficult to fuse and vaporize.

If between the two oxide electrodes a small, even a hardly perceptible, current passes, the joulean heat developed thereby in the intervening gaseous space will occasion a steady and rapid increase in the temperature and thus in the conductivity of the gases. The potential e at the electrodes accordingly falls from the value E until at $e = \frac{E + m}{2}$ an arc discharge is set up.

From the above it will be seen that the action in starting an oxide arc, eventually by means of an auxiliary flame, is the reverse of that followed in contact starting, namely, in the direction of arrow II on Fig. 37.

It should be noted, moreover, that a characteristic property of metallic oxides plays an important part in the starting of arcs of the second class, such as described by the author.*

The cathodic potential fall for red-hot oxides (calcium oxide, zirconium oxide, etc.) has an extraordinarily low value, something like 3.6 volts. Oxide electrodes possess the peculiarity of "emitting negatively charged electrons" (cathode rays), a property of which Wehnelt † has subsequently made use in his cathodes for vacuum tubes and his electric oscillation valve. (cf. § 3, page 8.)

* German Patents Nos. 117214; 137788 (1899); E. T. Z., **22**, pp. 155 (1901); Ann. d. Phys., **9**, 164 (1902).

† Erlanger, Ber., p. 150 (1903).

Generally speaking, incandescent metallic oxides have the property of making adjacent gases electrically conductive by ionization. Thus spark discharges can be produced even between metallic terminals at abnormally low differences of potential (cf. Chapter V, pages 62 and following) by the simple expedient of placing in their neighborhood incandescent metallic oxides of the kind mentioned.*

§ 25. Theoretical Discussion of the Characteristic Equation.

The characteristic equations of S. Thompson and H. Ayrton without doubt agree well with empirical results within a narrow, sharply defined range of application, and are capable — as shown in the foregoing — of furnishing an answer to a number of important practical questions.

It should be kept in mind, however, that the four arbitrary constants used in arriving at the three quantities e, J and L are purely empirical in their character and tell us nothing of their relation to the electrical quantities in the external circuit, i.e., to the voltage E and resistance R of the generator (eventually of the supply circuit) and the series resistance. There is little doubt, however, that the constants of the characteristic, the minimum potential m_0, as well as the factor δ, are numerically dependent on the electrical quantities in the external circuit.

In a strict sense the numerical constants in the Ayrton equation are valid only in connection with the particular generator used, the voltage supplied by it, $E = 150$ volts (approx.), and its internal resistance which latter unfortunately has not been recorded.

In addition to the considerations already pointed out the following theoretical criticism would seem to be in place.

* Ann. d. Phys., 11, 202 (1903).

Differentiation of the characteristic equation

$$e = m + \frac{C}{J} \tag{1a}$$

gives

$$\frac{\partial e}{\partial J} = - \frac{C}{J^2}. \tag{1b}$$

The relation to the quantities in the external circuit, namely the electromotive force E of the generator and the resistance of the outer circuit, generally requires that

$$E - e = JR.$$

Accordingly

$$\frac{\partial e}{\partial J} = - R. \tag{2}$$

From equations (1) and (2), thus, it follows that

$$\frac{\partial e}{\partial J} = - \frac{C}{J^2} = - R.$$

It is evident that — leaving out any eventual arbitrary constant — the quotient

$$\frac{C}{J} = JR,$$

or, in other words, that it is a function of the resistance.

In the characteristic

$$e = m + \frac{C}{J} = m_0 + \alpha L + \frac{\gamma + \delta L}{J},$$

the hyperbolic shape of the curves (see Fig. 22) is dependent on the denominator of the fraction $\frac{C}{J}$, i.e., the current J, consequently on a purely optional condition.

In reality, however,

$$\frac{C}{J} = JR\,(\phi L)$$

is a linear function of JR, that is, on the one hand, a linear function of the potential fall $(E - e)$ in the external resistance of the lamp circuit and, on the other hand, of the arc length L.

The hyperbolic form of the characteristics thus is due to the purely formal property of inverted functions, i.e., the fact that reciprocal values of straight lines produce hyperbolas.

Bearing in mind the fact that the values J, which appear as denominators in the second member of the characteristic ((1a), page 114), are dependent on the arbitrary quantities in the external circuit, i.e., on the electromotive force E of the generator and the ohmic resistance (or the apparent resistance $R = \sqrt{R_0^2 + (2\pi\nu S)^2}$), the arc voltage e is a linear function of the term JR. It is, consequently, determined by the arbitrarily chosen series resistance R.

In Fig. 38 the arc voltage e has been plotted against external resistance R (or JR), the current being constant at $J = 4$ amperes. Hertha Ayrton's experimental data (see Table 19) have been made use of.

We see from this that the arc voltage e — as is self-evident, if we stop to consider — is a linear function of the series resistance R, and that an extrapolation of the curve to $JR = 0$ would give us $e = E$.

Numerically, according to Fig. 38, we would get $e = E = 150$ volts, the supply voltage, which figure agrees with that mentioned casually by H. Ayrton as the electromotive force of the generator used by her.

By apparently eliminating the conditions existing in the outer lamp circuit (i.e., E and R) the Ayrton equation sets up the claim to describe, absolutely, the mechanism of the arc discharge for any given kind of electrode, and to be valid for all values of current.

In reality, in view of what has been set forth in the

TABLE 19. EXPERIMENTAL DATA USED AS BASIS FOR H. AYRTON'S CHARACTERISTIC.

Solid carbons. Positive 11 mm.; negative 9 mm.

Arc length L'.	1.0 mm.		2.0 mm.		3.0 mm.		4.0 mm.		5.0 mm.		6.0 mm.		7.0 mm.	
Current J, amperes.	e volts.	K.	e volts.	K.	e volts.	K.	e volts.	K.	e volts.	K.	e volts.	K.	e volts.	K.
2	50.6	0.0396	59.4	0.0337	66.75	0.0300	74.1	0.0270	81.4	0.0246	....	.....	....	.....
3	48.3	0.0621	53.75	0.0559	59.5	0.0505	65.1	0.0461	70.7	0.0424	76.1	0.0394	81.1	0.0370
4	46.5	0.0860	51.2	0.0782	55.9	0.0716	60.6	0.0660	65.3	0.0613	69.6	0.0575	74.4	0.0538
5	45.4	0.1100	49.6	0.1010	53.6	0.0934	57.9	0.0864	62.15	0.0805	65.9	0.0760	70.1	0.0714
6	44.65	0.1346	48.5	0.1238	52.25	0.115	56.15	0.107	60.0	0.100	63.5	0.0945	67.6	0.0888
7	44.1	0.159	47.8	0.147	51.3	0.137	54.9	0.128	58.4	0.120	61.7	0.114	65.6	0.108
8	43.7	0.183	47.15	0.170	50.5	0.159	54.0	0.148	57.3	0.140	60.5	0.132	64.1	0.125
9	43.4	0.208	46.7	0.193	49.9	0.181	53.3	0.169	56.4	0.160	59.6	0.151	62.9	0.143
10	43.1	0.232	46.3	0.216	49.4	0.202	52.7	0.190	55.7	0.179	58.8	0.170	61.9	0.162
12	42.6	0.282	45.65	0.264	48.7	0.246	51.7	0.232	54.6	0.220	57.6	0.208	60.5	0.198
14	42.25	0.332	45.25	0.310	48.2	0.290	51.0	0.274	53.85	0.260	56.7	0.247	59.5	0.236
16	.....	.....	44.75	0.358	47.8	0.335	50.5	(0.317)	53.25	0.300	56.0	0.286	58.75	0.272
$\beta = \frac{\Delta K}{\Delta J}$ (approx.).	0.0246		0.0232		0.0218		0.0207		0.0198		0.0190		0.0181	
$n = \frac{1}{\beta}$.	40.6		43.1		45.7		48.3		50.4		52.6		55.2	

foregoing, it is not at all permissible to assume that the constants in the equation are valid for any and all values of the electrical quantities in the external circuit.

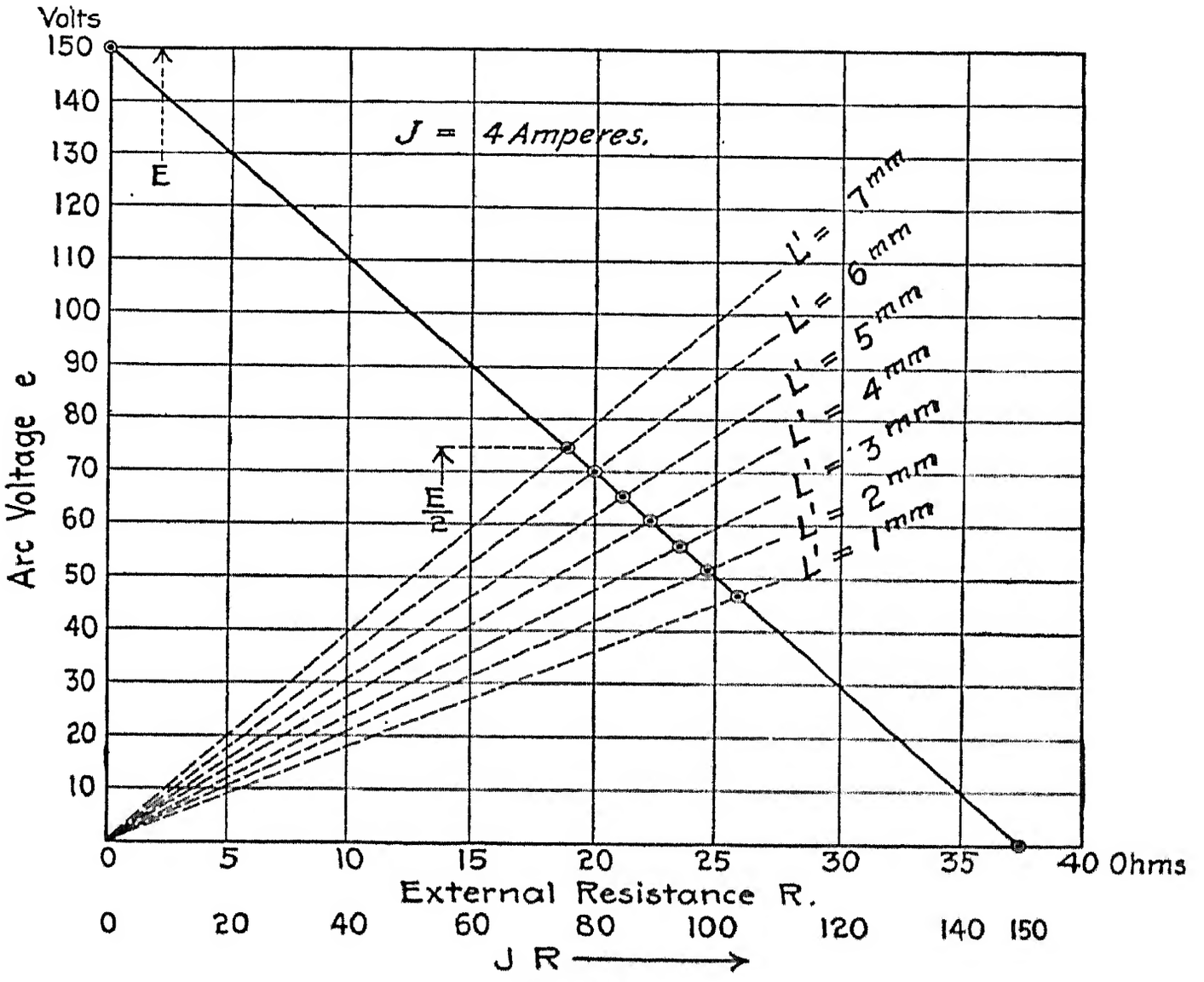


Fig. 38.

§ 26. The Resistance Effect (ρ) of the Arc.

The glowing gases in the arc possess a certain conductivity and, thus, the arc, *per se*, introduces in the circuit an actual resistance ρ which — rather incorrectly — it is customary to refer to as the apparent resistance.

It would seem to be better to designate it "resistance effect" ρ.

If the functional relation of the characteristic be known,

this resistance effect ρ can be treated arithmetically just like an ohmic resistance, i.e.,

$$J = \frac{E}{R + \rho} \quad \text{and} \quad \rho = \frac{e}{J}.$$

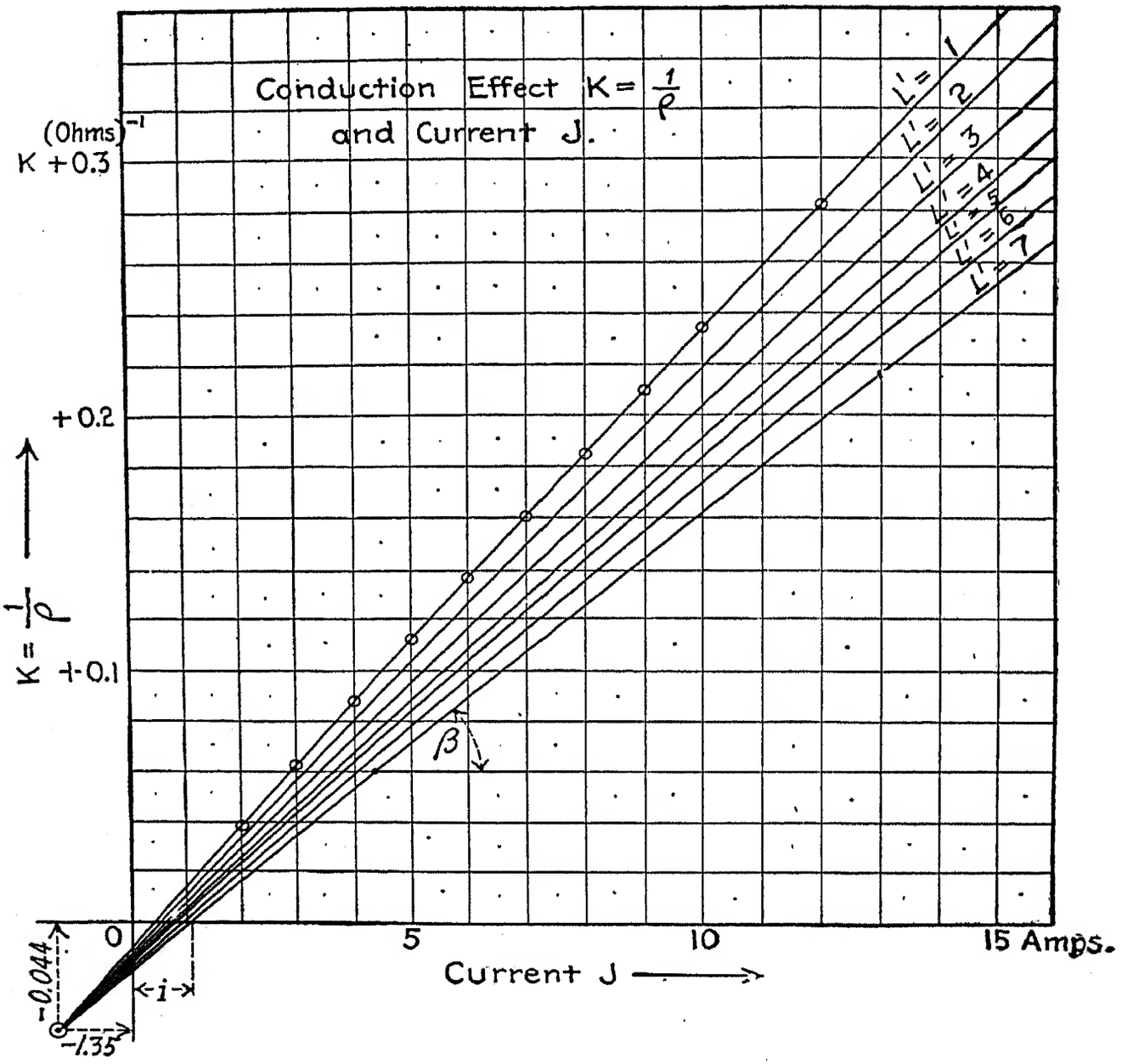


FIG. 39.

It is advantageous, however, in investigations of the mechanism of discharges, to use the reciprocal value of the resistance effect

$$K = \frac{1}{\rho} = \frac{J}{e},$$

which, for the sake of brevity, might be called the "conduction effect" K.

In Table 19 are given values of K, calculated from the experimental data published by H. Ayrton,* and which have served as foundation for the Ayrton equations and coefficients.

If the conduction effect $K = \frac{1}{\rho} = \frac{J}{e}$ be plotted as a function of the current J, it becomes apparent (Fig. 39) — as far as the available experimental data permit conclusions in this respect — that the conduction effect of the arc is a linear function of the current J in such a manner that

$$\beta = \frac{dK}{dJ} = \text{const.} \quad (L' = \text{const.})$$

This relation is corroborated for an arc length $L' =$ 4 mm. by the values in Table 20 which for

$$\beta = \frac{\Delta K}{\Delta J} \text{ are practically constant.}$$

It must be left practically undecided whether the small variations in the value of β (from 0.0192 to 0.0215) are physically significant or whether they are due merely to experimental errors, — eventually, to the graphical method of equalizing observation data.*

At any rate, the Ayrton constant (column 5)

$$\frac{1}{C} = \frac{dJ}{de} \times \frac{1}{J^2}$$

* The figures given by H. Ayrton (Table 19) are not those of the values actually observed, but graphically derived values from the test curves. Nevertheless, they probably belong to the most accurate and careful observations that have ever been made on this subject.

shows a not inconsiderable variation in value, numerically, from 0.0165 to 0.0198.

TABLE 20. LENGTH OF ARC, $L' = 4$ mm.

Current J, amperes.	Arc voltage e, volts.	$K = \frac{J}{e}$.	$\frac{\Delta K}{\Delta J} = \beta$.	$\frac{dJ}{de} \times \frac{1}{J^2} = \frac{1}{C}$.
2	74.1	0.0270	.....	.....
3	65.1	0.0462	0.0192	−0.0178
4	60.6	0.0660	0.0198	−0.0181
5	57.9	0.0864	0.0204	−0.0183
6	56.15	0.1070	0.0206	−0.0189
7	54.9	0.1277	0.0207	−0.0189
8	54.0	0.1481	0.0204	−0.0198
9	53.3	0.169	0.0210	−0.0198
10	52.7	0.190	0.0210	−0.0185
12	51.7	0.232	0.0210	−0.0165
14	51.0	0.2745	0.02125	−0.0169
16	50.5	0.3175	0.0215	−0.0178
		Average	0.0207	

One essential practical conclusion may be drawn, however, from the above analysis, namely, that the conduction effect of the arc becomes nil for a certain finite value of the current ($J = i$), a critical value at which, therefore, the character of the discharge becomes unstable.

Graphically this critical minimum current is represented by the distance i which the K curve (Fig. 39) intercepts on the abscissa (J).

This result agrees with the deductions from Kaufmann's conditions for stability (§ 24, page 106), according to which there exists a limiting value i of the current below which an arc discharge cannot be maintained, corresponding to $K = \pm 0$ and $\rho = \pm \infty$.

According to Fig. 39 the electrical relations in an arc are expressed by an equation of the form

$$K = \beta (J - i). \qquad (1)$$

Since the conduction effect $K = \frac{1}{\rho}$, according to our definition, is equal to $\frac{J}{e}$, it follows that

$$\frac{J}{e} = (J - i), \tag{2}$$

$$e = \frac{1}{\beta\left(1 - \frac{i}{J}\right)} \frac{n}{1 - \frac{i}{J}}, \tag{3}$$

$$\left(n = \frac{1}{\beta}\right) = \text{constant.}$$

It is evident from the characteristic, in form of equation (3), that when $J = \infty$ the arc voltage e will have a limiting value

$$e = \frac{1}{\beta} = n,$$

which value numerically approximates H. Ayrton's minimum voltage m and physically is identical therewith.

On the other hand, it follows that at a finite critical value of current, $J = i$, in the sense used in the foregoing, the arc voltage e assumes a value mathematically and physically discontinuous, or, in other words, infinite.

But whereas according to the Ayrton equation this discontinuance ($e = \infty$) occurs at $J = 0$, a characteristic in the form of equation (3) would seem to indicate that the discharge disappears already at a finite value of the current, the limit value $J = i$. Referring to Fig. 39 it will be seen that the values of i lie between 0.5 and 1.1 ampere and for a 4-mm. arc the value is approximately 0.81 ampere.

If we imagine the arc replaced by an ohmic resistance

ρ in the circuit (Fig. 21) the above statement would mean that in a circuit of infinitely high resistance ($K = 0$) a finite current i could exist at this point. This would actually be possible if, for example, a shunt of some kind were connected across this portion of the circuit (e, L; Fig. 21).

At any rate it seems a highly necessary precaution in tests intended to furnish data for characteristic curves to avoid the use of shunt or differential regulating mechanisms, and to make correction in the results for the necessary voltmeter connection. Whether due attention has been paid to these precautionary measures in the data published cannot now be ascertained.

As shown by the curves (Fig. 39) the minimum voltage $n = \frac{1}{\beta}$ increases with increasing arc lengths and, using H. Ayrton's values in Fig. 40, we find that

$$n = n_0' (1 + 0.0633 L') \text{ (approx.)},$$

where $n_0' = 38.2$ volts and L' is the apparent arc length. Referred to the true arc length L the value n_0 will be about 35.3 volts, if for the depth h of the crater we assume a mean value $h = 1.13$ mm. (approx.) and apply this to H. Ayrton's experimental data.

It may appropriately be remarked here that in deducing equations to express physical phenomena the use of linear equations (cf. § 20, pages 82 and following; Figs. 27, 28 and 40) — from which, for example, H. Ayrton's formulas, as a rule, have been evolved — requires great caution.

As a general statement it may be said that the differential coefficient $\frac{dy}{dx}$, i.e., the slope tangent of a $\phi(y, x)$-curve, is fairly suitable to describe, approximately, the physical aspects of the experiments.

A certain latitude is permissible in regard to extrapolation of data, when linear functions are not involved, as for example in case of parabolic functions in which, when $x = 0$, $y = 0$ also.

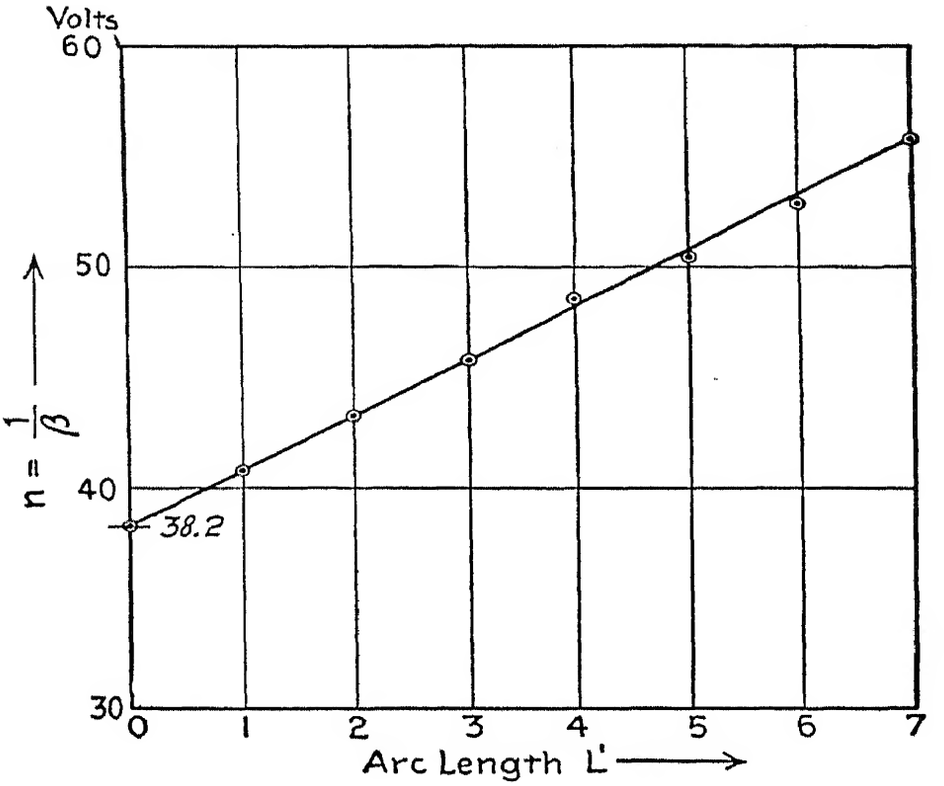


FIG. 40.

Quite otherwise is the case, however, especially in examples of the last-mentioned kind, in regard to the arbitrary constants which are represented graphically (cf. Figs. 27, 28, 39, 40) as extrapolated interceptions of the x-axis or the y-axis. Very often there is no definite physical meaning attached to these constants. The introduction of such constants sometimes has the effect of excessively complicating an otherwise simple physical phenomenon, if linear equations enter into the construction of other formulas. For instance, if they appear in the denominator they always will lead to asymmetrical hyperbolas.

If — as in the present example (Fig. 40) — it is a case

of arriving at a constant having physical significance, the minimum voltage n_0 (or m), it is to be noted that when an arc increases in length its cross-sectional area does not remain constant, as Ohm's law presupposes, but increases, also. It is not permissible to assume — without sufficient test — that the resistance of the gas volume between the electrodes increases as a linear function of their distance apart, as this would justify the further assumption that the current filaments of the arc flame spread out laterally when the arc length increases, which would result in the configuration of the arc flame remaining geometrically similar.

In such case, for example, the relation between minimum voltage n and arc length L would be expressible also by the equation

$$n = \pm n_0 \sqrt{1 + \alpha L}, \qquad (4)$$

as exemplified by Table 21.

TABLE 21.

Length of arc.		Minimum potential n, volts.	$\alpha = \frac{n^2 - n_0^2}{n_0^2 L}$.	
L' mm.	L mm.			
1	2.13	40.65	0.193	$n_0 = 34.25$
2	3.13	43.1	0.185	
3	4.13	45.7	0.189	
4	5.13	48.3	0.193	
5	6.13	50.4	0.190	
6	7.13	52.6	0.191	
7	8.13	55.2	0.197	
		α = const. = approx. 0.191		

Using this value, $\alpha = 0.191$, we get for the minimum voltage $n_0 = 34.3$ volts, a value which is considerably lower than that given by H. Ayrton ($n_0 = m_0 = 38.88$ volts).

The double sign used in the above equation (4) is not without physical justification, since if both electrodes are made of the same kind of material current transfer is possible in both directions.

From this it would follow that the characteristic as expressed by equation (3) (page 121) can have either plus or minus sign, which seems plausible also from a physical point of view.

§ 27. Minimum Current. Saturation Current.

As will be evident from what has been said in the foregoing, it is not to be expected that by it the question of a characteristic equation for expressing the mechanism of arc discharges has received a final and satisfactory answer. The theoretical and practical value of such an answer can hardly be overestimated, as by means thereof we would be able to make predictions of results in a domain that lies essentially outside of the conventional limits for industrial investigation and everyday problems.

Taking into consideration the remarks in connection with equation (4) (page 124), equation (3) (page 121) can be written, with double sign,

$$e = \pm \frac{n_0 \sqrt{1 + \alpha L}}{1 + \frac{i}{J}}, \qquad (1)$$

and is graphically represented in Fig. 41 (page 133).

This equation does not at all claim to be a perfect expression for the discharge characteristic; but it does indicate certain limiting conditions and the close relationship of two apparently very different forms of discharges, namely, on the one hand, the mechanism of conduction within dielectrics (insulators), and on the other, that of arc flames.

Knowledge of the phenomena in question is of special practical importance, for instance, in connection with accidental arcs occurring in " short circuits " which may cause the destruction of the insulation of two adjacent leads between which there exists a certain difference of potential, often seriously endangering the whole electric plant.

Equations (3) (page 121) and (1) (page 125) interpreted by Fig. 41 give us the following information.

If two opposite electrodes are separated a distance L, by a poorly conductive solid, liquid or gaseous medium, the current transfer between the electrodes possesses two characteristic phases (I and II, Fig. 41). In contradistinction to materials of high conductivity (metals), Ohm's law does not apply to this form of conduction, i.e., the postulate of electrical conduction in its simplest form,

$$\frac{J}{e} = K = \text{const.},$$

— namely, that the current (J) is directly proportional to the voltage drop (e) between the electrodes — is no longer sufficient. For that matter, even for metallic conduction, this expression requires qualification in case of alternating-current discharges.

Furthermore, in the case of conductors poor in ions, i.e., the poorly conductive dielectrics (solid, liquid or gaseous insulators), the following facts are known from J. Schröder's * investigation of a liquid dielectric, ethyl ether (Table 22, page 128).

The strength of the current J, to be sure, increases with increase in voltage, though not at a rate proportional to the difference of potential, e, between the electrodes — as demanded by Ohm's law — but more and

* Ann. d. Phys., 26, 597 (1908).

more slowly; i.e., the conduction effect K in an ohmic sense $\left(K = \frac{J}{e}\right)$ decreases with increasing voltage (e) and current (J) (cf. Table 22, on the next page, column 4).

More specifically, the conduction effect K — as far as the degree of precision of the data permits us to draw conclusions — decreases as a linear function of the current, and $\frac{\Delta K}{\Delta J} = \beta$, or $\frac{\Delta J}{\Delta K} = n$, is approximately constant (cf. Table 22, test record II, column 5), as is also assumed in our equation (3) (page 121). However, while in ordinary arc discharges the conduction effect K increases with the current, as shown by Fig. 39 (page 118), in the case of ethyl ether $\frac{J}{K} = n$ is of negative sign.

Pure dielectric conduction thus seems to be accompanied by the separating out, under the influence of the electrostatic field, of certain dissociated foreign bodies which act as carriers of the current. During a long-continued passage of a current of less value than the saturation current value (i) (see further below) there seems to take place, to a certain extent, an electrical purification of the dielectric and as a result the resistance of the latter rises considerably, as is shown by a comparison of the K values in test records I and II, Table 22.

The following discussion will further illustrate the mechanism of electrical conduction.

If the K values in Table 22 be plotted as a function of J, it will be found that the K curve cuts the J abscissa at a quite definite value, $J = i$, the so-called " saturation current " (i).

At this finite value of current the potential reaches a critical value $\pm \infty$ in the same way as we found in the

case of arc discharges (cf. page 121; also Fig. 39). The latter form of conduction, according to all probability, is purely or mainly a thermodynamical process. In contradistinction to this is the potential fall which takes place below the critical value of "saturation current" ($J < i$) for which the name "dielectric conduction" would seem to be suitable.

TABLE 22. CONDUCTIVITY OF ETHYL ETHER.

Test record, No.	Potential drop e, volts/cms.	Current J, amperes.	$K = \frac{J}{e}$, cm.³/ohms.	$\frac{\Delta J}{\Delta K} = n$.
I	....	.....	.....	.....
	667	18.8×10^{-10}	$(2.82) \times 10^{-12}$	.....
	1333	32.3×10^{-10}	2.42×10^{-12}	.....
	2000	41.2×10^{-10}	2.06×10^{-12}	.....
	2667	46.9×10^{-10}	1.76×10^{-12}	.....
	3333	52.1×10^{-10}	1.57×10^{-12}	.....
	4800	58.4×10^{-10}	1.22×10^{-12}	.....
II	....	.....	.....	.....
	667	6.1×10^{-10}	0.915×10^{-12}	
	1333	$(8.5) \times 10^{-10}$	$(0.637) \times 10^{-12}$	-1170
	2000	10.6×10^{-10}	0.530×10^{-12}	
	2667	11.7×10^{-10}	0.439×10^{-12}	-1210
	3333	12.5×10^{-10}	0.376×10^{-12}	-1270
	4800	13.4×10^{-10}	0.280×10^{-12}	-933

These two forms of conduction apparently take place under opposite sign. The "saturation current" (i) of the dielectric discharge probably is identical with the minimum current (i) which, as we have found in the foregoing, is a necessary condition for starting disruptive discharges (spark discharges, arc discharges, etc.).

The mechanism of electrical conduction through media poor in ions (insulators) thus would be represented by Fig. 41 (page 133) which has been plotted on the basis of equation (3) (page 121) or equation (1) (page 125).

As will be seen, with increasing electrode voltage the increase in current (J) is slower and slower until, as the voltage asymptotically approaches the value $e = \infty$, it reaches the finite value i.

The saturation current i (corresponding to the minimum current of arc discharges; cf. § 26, pages 117 and following) therefore is characteristic of the state of quasi-perfect insulation, such as is demanded of commercial insulators, as well as of the condition obtaining when puncture of the insulating material takes place and an arc discharge (short circuit) is set up.

The abscissa $J = i$ (Fig. 41) thus constitutes the asymptote which forms the boundary line between the domain of dielectric conduction (phase I, $J < i$) and that of electrolytic or thermodynamic conduction (phase II, $J > i$) in which latter occur the various kinds of arc discharges (short circuits, carbon arcs, etc.).

The outbreak of an arc — or of a disruptive discharge following the puncture of a dielectric — thus may be illustrated as follows:

If the temperature of the dielectric and all other conditions be kept constant we will observe, as the voltage (e) between the electrodes increases, values for current J that lie in phase I as long as J is less than the value (i) which is a quantity depending on the material and the temperature of the dielectric medium.

We have now reached a value of current J which is not far from the saturation current i.

The accidental or intentional introduction of a few conductive particles (ions) into the electrostatic field of the dielectric is now sufficient to raise the current above the unstable limit value (i) of the saturation current, thereby starting, with explosive abruptness, phase II which is characteristic of ordinary arcs as well as of the

disruptive discharge which accompanies the short-circuiting of insulated conductors.

This inoculation of the electrostatic field with a few ions, which suffice to produce a disruptive discharge in most cases, is caused by local heating of the nonconductive medium, since the dissociation of neutral dielectrics (gases, liquids, solid nonconductors, metallic oxides) is enormously affected by the temperature (see further below).

Both the starting of arcs proper and the unintentional arcs occurring in short circuits between insulated conductors are conditioned mainly by the temperature of the medium* and by the exceedingly rapid increase of conductivity with rise in temperature of the medium between the electrodes.

This great influence of temperature on the dielectric conductivity makes it difficult to obtain an insight into the mechanism of conduction through incandescent gases, which is of great importance for a knowledge of the arc. The difficulty is emphasized by the facts that it is hardly possible to keep the temperature of the conducting gases constant and that when it comes to determining the temperature of the active elements (the ions) within the dielectric all the usual methods for thermometric measurements fail.

That in reality — as has been tacitly assumed in the

* In connection with the insulation of high-tension transmission lines attention must be given also to some other factors such as moisture on the surface of and eventually within the interior of hygroscopical insulating materials (cf. Benischke's "Grundlagen der Elektrotechnik," **236,** 465). Perfectly pure water, of course, is an excellent insulator; but by acting as a solvent for metallic compounds (salts, etc.) and by hydrolytic ionization thereof, the presence of water containing even minute quantities of impurities will have practically the same effect as though the insulating dielectric itself were inoculated with conducting particles (ions).

foregoing — the conduction through incandescent gases follows the same laws as those which govern the conduction in solid or liquid dielectrics (ethyl ether, Table 21) is made very probable by the fact that arc discharges (cf. § 26, pages 117 and following, Fig. 39, Table 20) follow the same equations (2) and (3) (page 121) that demanded the existence of a critical value of current, the saturation current or the minimum current, i.

P. G. Nutting * has investigated luminous discharges through capillary helium tubes 3.12 mm. in diameter and 50 mm. long. From his results have been calculated the figures given in Table 23.

TABLE 23. VARIATION OF CONDUCTIVITY AND LIGHT OF HELIUM.

Gas pressure: $p=5.6$ mm. Hg.

1	2	3	4	5	6	7	8
Potential gradient e, volts/cm.	Current J, amperes.	Light intensity, hefner candles, HK.	Efficiency in HK per watt.	Conduction Effect $K=\frac{J}{e}$, in ohms^{-1}.	$\beta=\frac{\Delta K}{\Delta J}$.	$n_0=\frac{J-i}{K}$	Remarks.
233	10×10^{-3}	0.39	0.169	43×10^{-6}	....	144	Value of i as used here, $i=3.8\times10^{-3}$ amps.
211	15×10^{-3}	0.68	0.215	71×10^{-6}	5.60	172	
198	20×10^{-3}	0.96	0.242	101×10^{-6}	6.00	170	
190	25×10^{-3}	1.23	0.259	132×10^{-6}	6.02	169	
185	30×10^{-3}	1.47	0.265	162×10^{-6}	6.00	168	
180	35×10^{-3}	1.69	0.268	194×10^{-6}	6.04	166	
176	40×10^{-3}	1.89	0.268	228×10^{-6}	6.08	164	
173	45×10^{-3}	2.09	0.268	260×10^{-6}	6.04	162	
170	50×10^{-3}	2.28	0.268	294×10^{-6}	6.08	161	

As shown by the data in column 5, the conduction effect K increases nearly proportional to the current (J). The values of $\frac{\Delta K}{\Delta J}$ in column 6 are all of the same order of

* "The luminous properties of electrically conducting Helium gas." (Bull. of the Bureau of Standards, Vol. 4 (4), p. 511, 1908.)

magnitude, practically constant, as required by equation (3) (page 121) and equation (1) (page 125).

The critical minimum current (or the saturation current i) in the present example, is about 0.0038 amp. and the constant n_0 about 164 volts/cm.

According to column 6 there is a certain increase of $\frac{\Delta K}{\Delta J}$ with the current J. However, this can just as well be due to the greater conductivity, at higher currents, of the glass walls of the capillary tube.

Referring to columns 3 and 4 it should be remarked here in passing that the luminous efficiency of gas discharges in Geissler, Tesla and other similar tubes is exceedingly low, as the author has pointed out repeatedly on other occasions.* Yet we continue to hear these sources of light referred to — without any justification whatsoever — as the light of the future.

The maximum efficiency attainable in the present case is roughly 0.341 hefner candles per watt which is considerably lower than that of the modern incandescent lamp.

Considering the mechanism of conduction in gases — dielectrics — the following remarks may be added, referring to our equation (1) (page 120) or, in another form,

$$K = \frac{1}{n}(J - i).$$

According to a law deduced by J. J. Thomson, the conductivity k of gases may be expressed in the form used by G. Mie,† viz.,

$$k = k_0 \sqrt{1 - \frac{J}{i}},$$

* See, among others, Zeitschr. f. Elektrotechn. u. Maschinenbau (Potsdam, 1903), 4 to 12.

† Ann. d. Phys., 26, 598 (1908). Cf. also, a complex expression given by G. Mie (ibid.) for the k function below saturation current, which expression, however, does not conform readily with the test data in Table 22 (p. 128).

where i means, as in the foregoing, the saturation current, and k_0 the conductivity of the medium for infinitely small values of current ($J = 0$).

We see, immediately, that Thomson's equation fails and gives imaginary k values in case of discharges where $J > i$, that is, greater than the critical saturation current; and from the standpoint of the arc-lamp engineer it is principally such cases that are of interest here

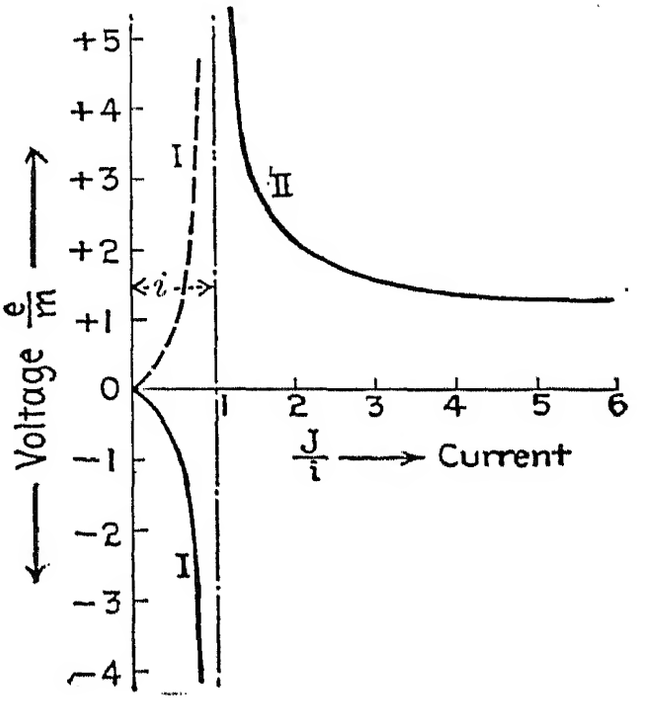


FIG. 41.

Now, in the light of the previous discussion (cf. page 129), it is true that the possibility that between the two phases I and II (see Fig. 41) which we have designated, respectively, as dielectric and electrolytic (or electrothermic) form of conduction, there may take place a change of polarity is not excluded. If, in accordance with this assumption, we give J in Thomson's equation double (resp. positive) sign, it would follow in phase II (which permits of a much more exact * experimental veri-

* From Table 22 (p. 128), Test Records I and II, we learn, for example, that below saturation value of current the conductivity is diminished by long duration of current, and thus depends on the earlier treatment or history of the material.

fication than phase I) that $\frac{\Delta K}{\Delta J}$ decreases with increase of current.

The phenomena taking place in the arc (cf. Table 20) as well as the results of the investigation of helium do not confirm this. On the contrary, they could rather be said to indicate that $\frac{\Delta K}{\Delta J}$ increases — even though ever so little — with increase in the current.

CHAPTER VII.

DISTRIBUTION OF THE ENERGY IN THE ARC.

§ 28. Importance of the Anode Crater. Anode Rays. Emission of Electrons.

In production of light by means of ordinary carbon arcs the positive electrode (the anode) plays an important part — not so much electrically as photometrically — since about 90 per cent of the total light proceeds from it.

On the other hand, and contrary to what is the case for flame carbon arcs, the radiation from incandescent gases is of comparatively little consequence in pure carbon arcs. The transformation of electrical energy into physiological effects takes place principally through pure temperature radiation, i.e., the radiation of a glowing solid: the anodic current base. In principle the mechanism of light production is essentially the same as for electric incandescent lamps (cf. § 8, page 24). The luminous efficiency of pure carbon arcs, therefore, is determined almost entirely by the energy density, and the consequent temperature, at the light-emitting surface of the anode crater.

It follows from this that for electrodes substances should be used which possess high melting and boiling points, and as low as possible specific heat. The latter property seems to be a physical quantity of paramount influence on the luminous efficiency of glowing solids (cf. Chapter I, § 12, page 39 and following).

A practical confirmation of this relation * is found, for

*Rasch, "Über die Grundbedingungen einer ökonomischen Lichterzeugung." Bayer, Industrie- u. Gewerbeblatt, p. 46 (1900).

example, in the high efficiency of the osmium lamp. The specific heat of osmium is 0.03113 (Regnault, $t = 50°$), while that of carbon, at the same temperature, is 0.199 (cf. Fig. 16, p. 43).

In this connection may be mentioned an empirical rule which H. F. Wiebe and Carnelley have formulated, but for which they by no means claim the authority of a physical law. However, it serves as a valuable guide in high-temperature engineering.

It appears that the temperature of fusion Θ of a substance is inversely proportional to its cubical coefficient of expansion α, its atomic (or eventually molecular) weight A and its specific heat c. Thus, according to H. F. Wiebe, for the majority of substances,

$$\Theta = \frac{1}{2.6\, A\, \alpha c}.$$

Another noteworthy relation has been found by Grüneisen, namely, that for any given substance (metal) the ratio $\frac{\alpha}{c}$ of the coefficient of expansion to specific heat c is constant for all temperatures, and thus independent of the temperature of the radiator.

In the case of ordinary carbon arcs the tip surface of the positive electrode becomes concaved something like the segment of a sphere, the radii of which center on the tip of the cathode (cf. Fig. 5, page 15; Fig. 8, page 18).

Now we know that, electrically, the real formation hearth of the arc, or of any other gaseous discharge, must be sought in the cathode. We know, further, that the cathode, when heated to a sufficiently high temperature, is capable of emitting cathode rays. From the fact that these rays can be magnetically deflected it may

be concluded that they consist of a stream of negatively charged particles, electrons.

The mass m of an electron is something like 1700 times smaller than that of the hydrogen atom. An electron at rest carries a free electrical charge, the so-called fundamental quantity of electricity,

$$\epsilon = 4.69 \times 10^{-10},$$

expressed in electrostatic units. (Planck.)

It has been shown, furthermore, that the ratio between this electrical elemental quantity ϵ and the ponderable or apparent mass m of an electron at rest is constant in value, no matter to what cause or what parent substance the electron owes its existence. However — as assumed by Weber (1846) in his "Atomic Theory of Electrodynamics," — this specific charge ϵ is dependent on the relative velocity of the moving elemental units of mass (the electrons).*

According to the latest views of science and experience, one is inclined to assume that Maxwell's "Electromagnetic Theory of Light" has been shaken to its very foundations and made to appear, through the conclusive experiments of Michelson, Morley, Trouton, Noble and A. H. Bucherer,† as "a theory long since exploded" (Bucherer). This theory of Maxwell's is based on the fundamental kinematical notion that radiation phenomena in the proper sense of the word (light) are to be conceived as vortical motion of the ether (by which conception kinematical explanations of a rather artificial

* Cf. "Prinzipien einer elektrodynamischen Theorie der Materie." Published by W. Engelmann, Leipzig, 1876.

† A. H. Bucherer, "Die experimentelle Bestätigung der Lorentz-Einsteinschen Theorie"; 80th Meeting of "Deutscher Naturforscher und Ärzte," in Cologne, (September 2–26, 1908). Cf. also Physikal. Zeitschr., 9 (22), Nov. 1, 1908, p. 755.

character have been substituted for the theory of " action at a distance ").

In the light of the latest investigations it is evident that Maxwell's physical world picture of electrodynamic phenomena — the high didactic value of which in numerous fields of application is beyond doubt — cannot claim, either scientifically or practically, to be of general importance for explanation of the mechanism of light.

In this connection, historic truthfulness compels us to remark that " Maxwell's electromagnetic theory of light " has never been productive of the least progress in the theory or the technology of light generation.

At any rate, the atomic-dynamic conception of matter, as advocated by Newton (1698),* Weber, Zöllner (1846), Lorentz and Einstein (1904) (corpuscular theory, emanation theory and electron theory) seems more promising for progress in the technology of light.

The essential teachings of the modern electronic theory culminate in the notion that mass (m) is closely connected with an electrical charge (ϵ); not only that, but that the so-called ponderable matter is a manifestation of electrical charges (Weber's postulate † of " elemental quantities of electricity ") or, conversely, that electrical charges

* Sir Isaac Newton, "Optik," 1698. 1704, Vols. II and III.

† It seems appropriate to mention here that for about 50 years W. Weber, together with Zöllner, attempted, without avail, to maintain against the teachings of the Maxwell school (Maxwell, Clausius, v. Helmholtz and others) his "electrodynamic atomic theory of matter" ("unit quantities of electricity," and the "principle of relativity"). (Cf. Weber-Zöllner's "Prinzipien," *l. c.* Leipzig, 1876). This controversy is not without its tragic side, since Zöllner, through certain formal corollaries of Weber's theory, became involved in the discussion of imaginary, abstract phenomena ("fourth dimension") and was charged with being mentally deranged (cf. v. Helmholtz). To such extreme consequences the modern Lorentz-Einstein's electronic theory could also lead by admission of velocities greater than that of light.

are identical with what we have been designating as ponderable masses. The modern electronic theory of Lorentz-Einstein (1904), defines the mass (m) and the charge (ϵ) of an electron by the equation *

$$\frac{\epsilon}{m} = \mathfrak{W}\sqrt[2]{1 - \frac{v^2}{c^2}}, \qquad (1)$$

in which v is the self-velocity, measured in the direction of propagation, of the elemental quantity of mass (the electron), c the velocity of light ($c = 2.99 \times 10^{10}$ cm./sec.) and $\mathfrak{W}$ a universal constant.†

The validity of Lorentz-Einstein's electronic theory may be considered as definitely proven in the most recent time, against the theory of Maxwell-Abraham (Kaufmann) by Bucherer's beautiful experiments (1908, *l. c.*).

The numerical value of Weber's constant $\mathfrak{W}$ has been determined, experimentally, to be

$$\mathfrak{W} = 1.730 \times 10^7$$

in electromagnetic units.

It can easily be seen that $\mathfrak{W}$ represents the universal relation between electric charge (ϵ) and the corresponding elemental mass (m), when the electric charge and the carrier thereof (m) are at rest ($v = 0$).

As is evident from equation (1) the fraction $\frac{\epsilon}{m}$ decreases in numerical value with increasing velocity (v) of the moving mass (m) and becomes zero when v is equal to a definite velocity $C = 2.99 \times 10^{10}$ cm. per sec., which

* It is evident, also, from this equation that under certain conditions ($v > c$) the so-called ponderable masses and real phenomena will assume — formally — imaginary physical forms: dangerous speculations to which Zöllner was a victim by his indiscreet introduction in mathematical equations of values of an astronomical order of magnitude.

† It would seem appropriate to designate this universal constant $\mathfrak{W}$ as W. Weber's constant.

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we have become accustomed to designate as the velocity of light.

There are numerous instances known to experimental physics (for example, anomal dispersion) where coefficients of refraction less than 1 occur. According to the undulatory theory this would mean that powerful disturbances, for which the velocity of propagation v is greater than the velocity c (the velocity of light), are possible.

It would seem almost self-evident that the velocity c, which we identify as the velocity of light, represents a quantity conditioned by cosmic causes. Thus a theory of light ought to take into consideration the fact that it is necessary to assume for the seat of all our physical phenomena and observations (i.e., the earth and the solar system) a definite self-velocity in absolute space (fall velocity), or — which means the same — for the ether (space) a definite, constant and considerable flow velocity relative to the ponderable masses of our solar system.

It has been shown (cf. § 3, page 8) that we possess in electrodes of the second class — oxide cathodes — a means which we were justified in designating as typical electron producers — eventually arc producers. More especially, in oxide electrodes we have to do with agents which are capable of splitting up the chemical atom, as hitherto understood, into elemental units of mass, electrodynamic or electrostatic in their nature.

It has been shown * that one can attain extraordinarily high energy densities and temperatures at the current bases of incandescent oxide electrodes — i.e., at the surface of transition between the current-carrying solid cathode and the current-carrying gas column, and that

* German Patents Nos. 117214 and 137788 (March, 1899); E.T.Z., 22, 155 (1901).

one can obtain vacuum discharges * as well as arc discharges of surprising beauty.†

If one observe a discharge of low current density from an oxide electrode in vacuo, the path of the electrons will be recognized by the fluorescence set up by them in the residual traces of gas within the vacuum tube. At low currents a bluish streak of light will appear. This is projected in a straight line perpendicularly to the cathode surface, but possesses great mobility when acted upon by an electrostatic or magnetic field.

The potential drop at the cathode current base is very small, amounting, in vacuo and at high temperatures, to about 3.5 volts or less.

With increase in the current density, the gas pressure being normal, the beam of cathode rays acquires greater rigidity and density. Since the kinetic energy of the electrons is received and absorbed by the gaseous particles that happen to be in their path, the latter become heated to an exceedingly high temperature.

The same is true of any solid body in the path of the

* E. Rasch, "Gasentladungen an elektrolytischen Glühkörpern," Ann. d. Phys., 11, 202 (1903). The same, "Gasentladungen und Lichtbogen mit glühenden Leiter zweiter Klasse als Strombasis," Phys. Zeitschr., 4, 375 (1904).

† Wehnelt — very much later — [Erlanger Ber. (1903), p. 150] also made electrical discharges from oxide electrodes the subject of an investigation, using platinum-foil electrodes covered with a thin layer of CaO. The relatively low melting point of the metallic support (platinum) for the active material (the oxide) permitted him to carry on the experiments only at relatively low temperatures, gas pressures and cathodic energy densities. That the author, in the published account (1899) of his electrical discharge experiments with oxide electrodes, could not make use of terms and explanations such as Wehnelt subsequently borrowed from the electronic theory, finds its very simple explanation in the fact that the modern electronic theory did not exist at that time (1899). The prior work by the author on oxide electrodes has been overlooked by Wehnelt and his disciples.

cathode rays — for example, the anode crater — on which the electron stream impinges.

On the other hand, the anode also * is the source of a stream phenomenon, although of another kind, consisting, as it does, of positively charged particles in motion. The anode rays (also known as atomic rays, canal rays or X-rays) differ from the cathode rays in that the carriers of the anode radiation are ponderable masses of the same order of magnitude as the chemical atom or molecule, whereas the moving elemental masses in the electron stream are a thousand times smaller than the smallest known chemical unit of mass, the hydrogen atom.

In anode rays the ratio between charge (ϵ) and mass (m) varies between $\frac{\epsilon}{m} = 10^1$ and 10^4 electromagnetic units.

In the case of electric arcs the separation of these two kinds of streams is ever so much more difficult than in vacuum discharges, since in the former diffusion, irregularities of the gaseous path and several other causes greatly complicate conditions.

Still the typical phenomena of a large-current electric arc may be illustrated in an instructive manner by a special arrangement (Figs. 42 and 43) originated by Gebr. Siemens. Fig. 42 represents a 150-amp. 80-v. carbon arc. The cathode K consists of a carbon pencil, only 11 mm. in diameter. This is surrounded, except for a short tip, by a protective jacket of a special refractory material, and is provided with metallic current connections (metal spirals). The anode A has a diameter of 38 mm.

By this construction the current density (amps./sq. mm.) at the thin cathode tip K can be given exceedingly high values. The energy density (watts/sq. mm.) at the

* E. Gehrcke and O. Reichenheim, Ann. d. Phys., 25, 861 (1908).

cathode remains tolerably low, since the cathodic drop is only a few volts.

We see from Fig. 42 that the cathode projects against the anode a beam of rays — reminding one of a steam nozzle — which, in the last analysis, are nothing but the tracks of the electrons emitted by the cathode.

The beam of rays impinges on the anode surface *A*, doubtless partaking in the heating thereof and suffering

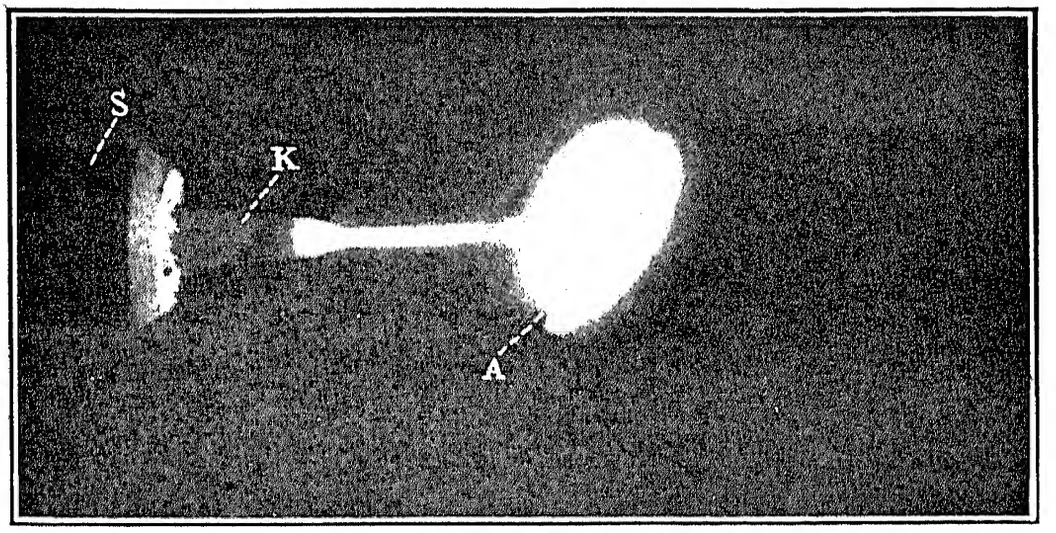

FIG. 42.

diffuse reflection from the white hot crater to an appreciable extent.

By measurement of the crater surface (or, rather, the projection of the crater edge) it was found, in the present case, that the current density was about 0.248 amp./sq. mm. However, the conical portion back of the crater edge, for a distance of about 4 cm., also showed a plainly outlined zone of deterioration.

The arc shown in Fig. 43 burned at 120 amperes and 80 volts at the terminals. The positive carbon was 33 mm. and the negative 10 mm. in diameter.

The cathode *K* is nearly at right angles to the anode *A*, and the beam of cathode rays from the former is deflected towards the anode by a magnet. By this con-

struction is avoided any obstruction of the light radiation from the anode crater, a feature which is of practical value for searchlights and similar apparatus.

The anode crater, consequently, constitutes a reflector for the cathode rays impinging thereon, as well as for the light rays. Without doubt the anode owes to the

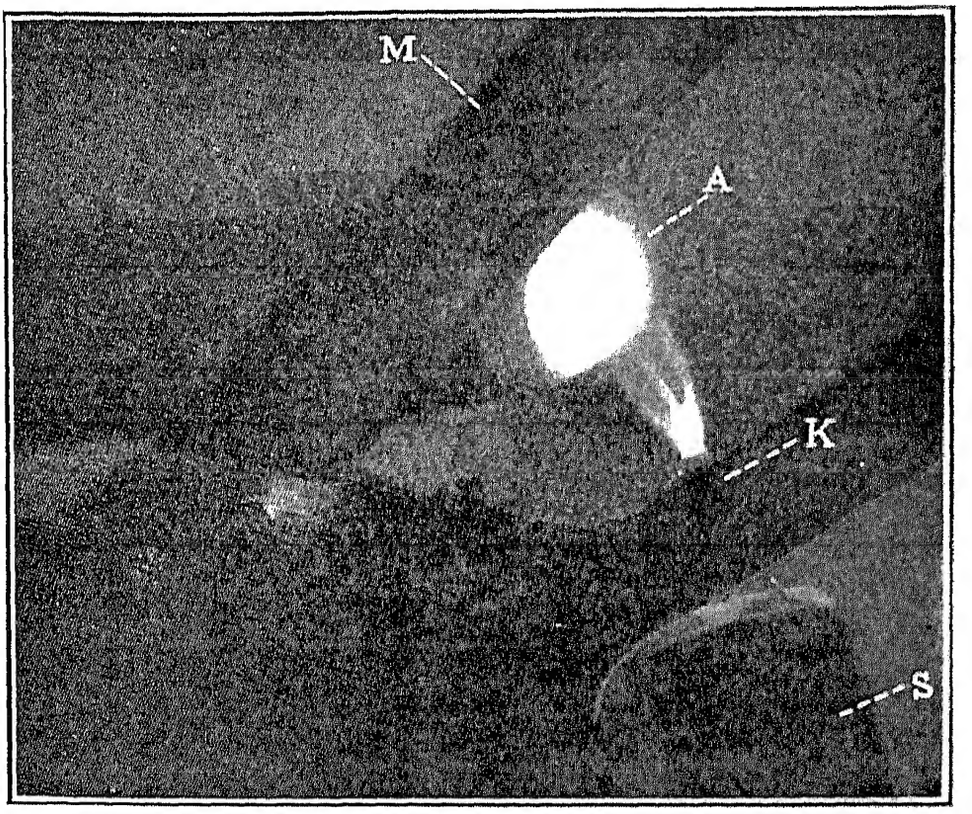

FIG. 43.

cathode a portion of its energy, temperature and radiation.

Conversely, some of the activity of the cathode is due to the kinetic and thermal energy of the radiation emanating from the anode reflector and striking against the cathode.

§ 29. The Current Density (s) at the Anode.

The formation of an anode crater is purely a matter of polarity and thus exclusively confined to direct-current arcs. In the case of alternating-current arcs both

electrodes assume approximately symmetrical shapes, on account of the continually changing polarity.

Apparently the formation of the positive crater is intimately related to the burning away and the oxidizability of the electrode material, i.e., to a specific property of carbon (cf. § 14, page 46 and following).

It is to be noted, furthermore, in regard to this crater formation, that the positive pole in electrolytic processes always is the seat of oxidation or combustion. This explains the considerable consumption of the anode as well as the fact that by excluding oxygen (as in the case of the enclosed arc) neither the anode crater nor the cathode point becomes very pronounced.

This view is further strengthened by the fact that as the current density and the arc length increase the crater becomes shallower and shallower until, finally, the anode crater is turned inside out, so to speak, and forms the frustum of a cone, the sides of which are freely exposed to attack by the oxygen in the air.

In the case of arcs between nonoxidizable electrodes (cf. page 6 and following) the author has never observed the electrode tips to shape themselves in this manner, which seems characteristic for carbon arcs. On the contrary the ends of electrodes made of substances — generally referred to as refractory — such as the oxides * of calcium, barium, strontium, yttrium, zirconium, cerium, lanthanum, thorium, magnesium and others, become more or less semi-fluid — according to melting point, boiling point and current density — and form bright, rounded tips, from the convex surface of which the current " lines " issue and enter the white glowing core of the gas column.

* The various oxides are enumerated here in the order of decreasing suitability as arc producers.

The manner of conducting the current to the active tips of oxide electrodes has been described more fully in another place.* Either the electrode is provided with a metallic core or is electroplated on the outside. In the immediate neighborhood of the white-hot electrode tip these metallic conductors are oxidized and fuse together with the electrode material proper.

It seems safe to assume, in agreement with experiments for which, again, we are indebted to Hertha Ayrton, that the crater spot f increases in size proportionally with the current J and the arc length L.†

This is verified by the figures in Table 24.

TABLE 24. RELATION OF CRATER SURFACE TO CURRENT (J) AND ARC LENGTH (L).

Negative, cored carbon: 13 mm. outside diameter, 3 mm. core.
Positive, solid carbon: 11 mm. diameter.

Arc length L'	1.00 mm.	2.00 mm.	3.00 mm.	4.00 mm.
Arc length L, approximate	2.36 mm.	3.15 mm.	3.98 mm.	4.85 mm.
Depth of crater h	1.36 mm.	1.15 mm.	0.98 mm.	0.85 mm.

Current J, amperes.	Crater surface f.			
	f sq. mm.	f sq. mm.	f sq. mm.	f sq. mm.
4	7.74	9.19	9.90	10.35
7	12.25	13.66	14.39	14.86
10	16.55	17.95	18.70	19.17
15	23.76	25.25	25.88	26.42
20	30.97	32.47	33.08	33.59
A	2.0	3.39	4.21	4.62

$$\phi = \frac{\Delta f}{\Delta J} = 1.455 \text{ sq. mm./amp. (mean).} \quad A = 0.984\, L.$$

* For further particulars in regard to the properties of electric arcs between oxide electrodes the author must refer back to the more detailed accounts. (Cf. § 3, p. 6.)

† This is contradicted by Granqvist according to whom the diameter of the crater $D = 1.70 + 0.32\, J$.

It will be noticed that the differential coefficient

$$\phi = \frac{\Delta f}{\Delta J}$$

is remarkably constant for all values of current and has a mean value

$$\phi = 1.455 \text{ sq. mm./amps.}$$

Thus, the crater surface increases according to the linear equation

$$f = A + \phi J \text{ (amps./sq. mm).} \qquad (1)$$

In this $A = aL$ depends on the arc length L and crater depth h, and is, in the present example, numerically, nearly identical with the length of the current path. $A = L = L' + h$ (see Table 24).

The current density s, referred to the surface projection f of the crater, consequently is

$$s = \frac{J}{aL + \phi J} \text{ (amps./sq. mm.).} \qquad (2)$$

We see from this that for constant length of arc L, the anodic current density s, with increasing current J rapidly approaches a limit value

$$\mathfrak{s} = \frac{1}{\phi} \text{ (amps./sq. mm.),}$$

which, for the particular grade of carbon here under consideration, is 0.69 amps./sq. mm. This limit value $\mathfrak{s}$ gives an indication of the *quality* (vaporization resistance) of the electrode material.

On the other hand, from equation (2), we get

$$s = \frac{1}{\frac{aL}{J} - \frac{1}{\mathfrak{s}}},$$

which tells us that the current density s in the anode crater decreases with increasing arc lengths L.

In the case of electrodes which are not in vertical axial alignment the conditions, obviously, become more complex, due to draft disturbances which tend to distort the arc upwards, thereby stretching the current lines of flux (the arc length).

TABLE 25. CARBONS CONVERGING UPWARDS AT AN ANGLE OF 45°.

Current $J = (9.75 \pm 0.25)$ amps. = const.

e, arc voltage, volts.	L', distance between electrodes, mm.	f, crater surface, sq. mm.	eJ, watts.	s, current density in crater.
61	3.5	6.0	595	1.63
72	9.0	9.75	701	1.00
78	10.0	10.0	760	0.975
90	12.5	10.6	877	0.920
94	13.5	10.6	916	0.920

Table 25 above contains experimental data determined by Andrews* for an arc of 9.75 amps., between electrodes converging upwards at an angle of 45 degrees.

Andrews' tests — in which, indeed, the true arc lengths were unknown — show, at least, that the current densities s decrease with increasing arc voltages e and arc lengths L'.

Now, since the luminous efficiency of the carbon arc is determined principally by the temperature and energy density of the light-emitting portions of the electrodes, it follows that artificial lengthening of the arc by magnetic blow or other drafts under certain circumstances will result in a lessening of the efficiency. This conclusion has been corroborated also for upwardly converging, mineralized carbons by Viertel's exhaustive investigations.

* M. L. Andrews, Engineering, **81**, 698 (1906).

The radiation from the luminous arc flame of mineralized carbons, thus, is not always sufficient to compensate for any considerable deficiency occasioned by artificial lengthening of the arc or by reduction of the energy density at the luminous tip of the solid electrode.

§ 30. Potential Drop at the Anode. Energy Radiated by the Anode Crater.

1. Anode Drop and Cathode Drop.

Strictly speaking the anode drop (e_1) is to be defined as the sudden lowering of potential which takes place at the transition of current from the solid electrode to the immediately adjacent gas stratum. Similarly, the cathode drop (e_2) is the difference of potential existing between the solid boundary surface of the negative current base and the gas layer infinitely close to it.

Obviously, a precise experimental determination of these potential drops meets with great difficulties. For one thing, the introduction of exploring rods in the current path distorts the electric field. For another, they carry away heat which results in a lowering of the temperature of the arc gases in their immediate vicinity.

For practical purposes it generally is sufficient to assume that the voltage drops dV of an elemental distance dx of the current path, i.e., the potential gradient $\rho = \frac{dV}{dx}$ is constant throughout the whole arc length. In other words, the complex conditions are provisionally simplified by considering the voltage drop inside the conducting gas column, as approximately a linear function. (See Fig. 44.)

The potential difference, as measured between the electrodes, thus is made up of the drop inside the arc

flame (e_3), the cathode drop (e_2) and the anode drop (e_1). This is illustrated in Fig. 44, for the particular case of a mineralized carbon arc 16 mm. long, according to data obtained by Jaschke.*

It is unfortunate that, even with this assumption, suitable data are not available for a satisfactory explanation of the salient facts. We are here, also, obliged to fall back on Mrs. Hertha Ayrton's valuable research work.

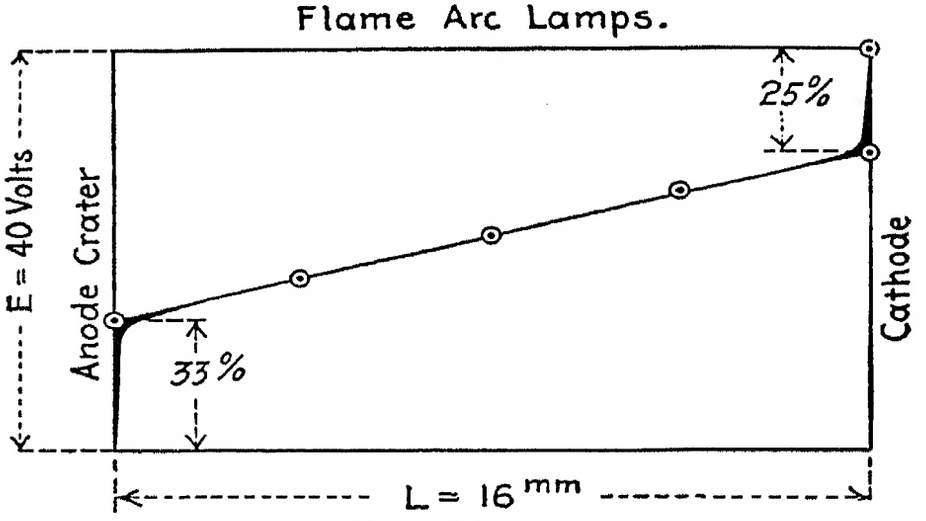

FIG. 44.

H. Ayrton, however, has not determined the actual anode and cathode drops (e_1 and e_2) but has measured the potential difference existing between an exploring electrode inserted in the middle of the arc, and the anode and cathode, respectively.

According to H. Ayrton the anode drop (e_1) of an arc between solid carbons (positive, 11 mm.; negative, 9 mm.) can be found from the empirical formula

$$e_1 = A' + \frac{B + DL'}{J}, \qquad (1)$$

in which $A' = 31.28$, $B = 9.0$ and $D = 3.1$. This formula may be used with the reservation pointed out above for

* Jaschke: "Spektrophotometrische Untersuchungen über den Einflusz der Beimischung von Metallsalzen zu Bogenlichtkohlen auf die Verteilung der sichtbaren Energie in den einzelnen Teilen des Spektrums ihrer Flammenbögen," p. 26 (Inaugural dissertation, Breslau, 1904).

a provisional elucidation of the essential conditions in the arc.

2. Radiation from the Anode.

The total energy $\mathfrak{Q} = Je$ converted at the current base of the anode, thus, may be expressed

$$\mathfrak{Q} = A'J + B + DL' \text{ (watts).*} \tag{2}$$

If from this equation we eliminate by differentiation the arbitrary quantity B, which has no physical significance, † it follows that

$$\left.\begin{aligned} d\mathfrak{Q}_1 &= A'dJ + DdL \\ &= 31.28\,dJ + 3.1\,dL. \end{aligned}\right\} \tag{3}$$

In the discussion and practical application of equations (2) and (3) it is to be noted that in stable discharges $\left(\frac{dJ}{dt} = 0\right)$ the value of the current J is conditioned, mainly by the voltage E, of the source and the amount of steadying resistance R, in series with the arc. Furthermore, according to the Ayrton characteristic, there obtains between arc length and current the relation

$$dJ = \frac{\delta}{e - m}\,dL,$$

and, in general,

$$\frac{dJ}{J} = \frac{dL}{L}.$$

* As before, L' here means arc length as used by H. Ayrton. Thus $L' = L - h$, where L is the true length of the gaseous current path. Since the depth h of the crater may be considered constant within the small change of the arc length from L to $L + dL$, we can write, also, $dL' = dL$.

† For current $J = 0$ the energy developed at the anode obviously must be $\mathfrak{Q}_1 = 0$, also; $(B = 0)$. If otherwise, it would indicate that the arc itself could be a source of current. Of course, it cannot be asserted, absolutely, that this really is impossible under any and all conditions. For example, it would seem feasible to reverse the thermodynamic cycle and maintain the phenomena at the cathode, anode and arc flame by a suitable supply of thermal energy.

§ 31. Hissing of the Arc.

The open arc, both alternating- and direct-current, produces, under certain conditions of current and voltage, a loud, hissing sound, resembling the noise made by steam escaping under high pressure from a nozzle.

This, at times, may be the cause of considerable annoyance and disturbance in lecture halls and similar places lighted by such lamps. The intensity of the sound increases with the current and frequently becomes intolerable in the case of high-current lamps, such as are used for searchlights, stereopticons and similar purposes.

The cause of hissing has been a frequent and favorite theme for discussion. Hertha Ayrton, among others,* has made a thorough investigatien of the subject. We must content ourselves here by giving the salient facts as briefly as possible.

H. Ayrton † summarizes her extensive observations on solid carbons (positive, 11 mm.; negative, 9 mm.) for the connection between the correlated and critical quantities e_k, J_k, L_k' (arc voltage, current and arc length), by the following empirical formulas:

$$e_k = 40.05 + \frac{2.91\,J_k - 29.02}{10.54 - 0.416\,J_k}\ \text{(volts)}, \tag{1}$$

$$e_k = 40.05 + 2.49\,L_k'\ \text{(volts)}, \tag{2}$$

$$L_k' = \frac{1.17\,J_k - 11.66}{10.54 - 0.416\,J_k}\ \text{(mm.)}. \tag{3}$$

These may be interpreted:

1. With constant distance between the electrodes (L' = const.) hissing will take place when the current J is increased above a certain value.

* Niaudet, Compt. Rend., 92, 711 (1881). Gime, Lum. El., 18, 556 (1885). Cross & Shepard, Proc. Amer. Acad., 22, (1) 227 (1886). Lecher, Wiener Ber., 98 (II a), 1192 (1889).

† H. Ayrton, Inst. El. Eng., 28, 400 (1899).

2. With constant current (J = const.) hissing will be produced if the arc (L) is reduced below a certain length.

3. When hissing occurs the characteristic fails as a law. The voltage takes a sudden drop of about 10 volts which is accompanied by a rise in the current of from 2 to 3 amperes.

The Ayrton values for the critical quantities L_k, J_k and e_k have been tabulated below. (Table 26.)

TABLE 26. HISSING RANGE OF DIRECT-CURRENT CARBON ARCS.

Solid carbons. Positive = 11 mm. Negative = 9 mm.

Critical.			Critical resistance effect of the arc,
Arc length L_k', mm.	Voltage e_k, volts.	Current J_k, amps.	$\rho_k = \frac{e_k}{J_k}$, ohms.
1	42.2	14.06	3.0
2	44.5	16.55	2.7
3	47.5	17.54	2.7
4	49.4	19.22	2.6
5	53.0	20.0	2.7
6	55.0	20.5	2.7
7	56.9	21.0	2.7
		Mean: 2.71	

In column 4 of Table 26 will be found the calculated values of the resistance effect of the arc $\rho = \frac{1}{K}$ in the sense in which this term has been used before.

Experimental data of the kind obtained in the present case are affected by numerous incidental conditions, more especially the shape of the anode, how long the electrodes have been burning, the purity of the carbon, etc. But even though they cannot be given the same weight as purely physical observations, H. Ayrton's data and

equations ((1) to (3)) may serve as a basis for the following general statement:

For any values of current, voltage and arc length, hissing will occur when the resistance effect of the arc, $\rho = \frac{e}{J}$, *becomes numerically smaller than a certain limit value* ρ_k, *characteristic for the particular quality of carbon used.*

As we see from Table 26, the above rule is confirmed by Ayrton's experimental results. These show that the value of ρ_k is practically constant for all critical arc lengths, currents and arc voltages. For the particular variety of carbon used in these experiments $\rho_k = 2.71$ ohms.

Thus, expressed in a different way, an arc will begin to hiss when its conductivity effect exceeds a certain value

$$K = \frac{1}{\rho} = \frac{J}{e}.$$

It has been pointed out already, by H. Ayrton, that the occurrence of hissing depends on the conditions in the external circuit. From the relations given above we are in a position to determine the values of the external resistance R (steadying resistance), and the external voltage E (generator voltage), which must not be exceeded in order to avoid hissing of the arc.

Since generally $J = \frac{E}{R + \rho}$, it follows that hissing will begin when

$$J = \frac{E}{R + \rho_k}.$$

As previously shown (cf. § 29) the anode crater, with a surface f, will, through the action of the current, automatically shape itself, so that for all arc lengths and current values

$$\frac{df}{dJ} = \phi = \text{constant.} \qquad (4)$$

The material constant ϕ is dependent on the density, the boiling point, the heat of volatilization and the *quality* of the carbons used.

If, now, the current density s at the anode crater be suddenly increased — for example, by switching other lamps in parallel, by failure of the regulating mechanism or by some other accidental circumstance — a turbulent volatilization will set in, "hissing," and will continue until the crater surface f has attained a size which is required for equilibrium (equation (4); see also § 29) and as long as the velocity of the material particles shot off from the anode is within the velocity limits of audible sound waves.

Thus, an arc will hiss when — and only when — the current density of the anode crater,

$$s \geqq \mathfrak{s}\left(1 - a\frac{L}{f}\right).$$

For the carbons used by H. Ayrton it was found (cf. § 29) that a was remarkably near 1 and that the maximum current density was

$$\mathfrak{s} = \frac{1}{\phi} = 0.688 \text{ amp. per sq. mm.}$$

The foregoing analysis of the phenomenon of hissing agrees with the explanation given by Luggin.* The latter concludes that hissing will occur when the anodic current density exceeds 0.5 amp. per sq. mm.

H. Ayrton draws from her extensive investigation of the subject the final conclusion that the determining causative factor in the phenomenon of hissing is the access of oxygen to the carbons and the oxidation process conditioned thereby.

* Luggin, Wien. Ber., 98 (II), 1192 (1889).

It is true that hissing does not occur with enclosed arcs. But in these the peculiarly shaped current base f of the electrodes (see Figs. 6 and 9) ordinarily is so large that it is practically impossible to exceed the maximum current density with the strength of current usually employed.

H. Ayrton's explanation appears inconclusive also, in view of the fact, established by the author, that oxide arcs will hiss when the current density is high (alternating current). In such arcs oxidation is evidently an impossibility, except the negligible oxidation of the metallic conductor core or coating.

§ 32. Energy Density (e_1) at the Anode Crater.

The energy density and temperature of the active electrode surfaces — the cathode point and the anode crater — are of paramount importance for the luminous efficiency of pure carbon arcs. Furthermore, in the case of direct-current arcs, by far the greater portion of the light is produced at the crater surface of the positive carbon.

In the foregoing (§ 29, page 144 and following) we found the current density

$$s = \frac{J}{f} = \frac{J}{aL + \phi J} \text{ (amps./sq. mm.)}.$$

Using temporarily H. Ayrton's data we have, for the anode drop,

$$e_1 = A + \frac{B + DL}{J},$$

where

$$A = 31.28,$$
$$B = 5.5,$$
$$D = 3.1,$$

and the true length of the arc, L, has been substituted for the apparent arc length L', as already explained.

The energy density per unit of crater surface $_q = \frac{Je_1}{f}$ consequently is

$$_q = \frac{AJ + B + DL}{aL + \phi J} \text{ (watts/sq. mm.)}. \qquad (1)$$

The energy density $_q$ thus represents the total energy radiated per unit of incandescent surface.

Numerically, H. Ayrton's data give for the anodic energy density,

$$_q = \frac{31.28\,J + 5.5 + 3.1\,L}{L + 1.455\,J} \text{ (watts/sq. mm.)}. \qquad (2)$$

From the above equation it follows that the energy density — and therefore the temperature and light efficiency — decreases with increasing arc lengths (L), but increases with increase of current (J). In the special case of H. Ayrton's carbons the maximum energy density was about 21.5 watts per sq. mm.

It has been determined photometrically that as a rule the brightness of the anode crater of a carbon arc is, in round figures, 120 *HK* per sq. mm. (Siedentopf). On the basis of this the specific luminous efficiency η of the anode crater of pure carbon arcs will be

$$\eta = \frac{120}{21.5} = 5.6\ HK \text{ per watt.}$$

It is noteworthy that for mercury vapor lamps operated at a high temperature, as well as for electrolyte-arcs,* the maximum efficiency (η) is of the same order — in fact, practically identical — namely, in round figures, 5.6 *HK* per watt.

In this connection it may be mentioned that the mean surface brightness of the sun, according to Fabry, is 1591 *HK* per sq. mm., or approximately 13 times as great as that of the anode crater.

* E.T.Z., 22, 155 (1901).

§ 33. Cathodes and Anodes of Fluid Lamps. Mercury Vapor Lamps. Electrolytic Solutions as Current Bases for Electric Arcs.

In the modern form of arc (as exemplified in the different types of flaming arc lamps), the part played by the current-carrying gas column (the flame) in the production of light can be materially increased by the introduction therein of volatile conductors of the second class * (metallic salts, oxides, fluorides, etc.). Such substances possess a distinctly selective emissive power,† i.e., they produce oscillations of certain wave lengths and frequencies which have a maximum physiological effect on the human eye.‡

Nevertheless, it would be erroneous to think that the luminous efficiency could be improved simply by lowering the temperature of the anode. This should never be done unless made necessary for other reasons. The energy consumption due to the anodic potential drop is quite considerable and the light emitted by the anode —

* Cf. Lummer, "Die Ziele der Leuchttechnik," p. 29. Published by R. Oldenburg, Munich, 1903.

† Transactions of the German Physical Society, 5, 284.

‡ The author takes this opportunity to call attention to the fact that ever since 1892 he has advocated the use of metallic salts for the purpose of producing flame arcs giving such selective radiation. (Patent Application R7687 VIII/21c., December 5, 1892. See also Lummer, "Die Ziele der Leuchttechnik," published by R. Oldenburg, Munich, 1903.)

As far back as 1898 the author demonstrated colored arcs produced by means of "salted" carbons ("Über die Erzeugung hoher Temperaturen." Lecture, illustrated by experiments, at Bayrisches Gewerbemuseum, Nov. 21, 1898).

H. Bremer's later utilization of this discovery (German Patent No. 114242, Nov. 30, 1899) was based on the assumption and contention that the introduction into the arc of conductors of the second class (metallic salts) would facilitate the melting and dropping off of any slag formed at the electrode tips. This evidently shows a misunderstanding of the principle of selective radiation, to which property the so-called "Bremer" lamps owe their commercial success.

which is a function of its temperature — materially contributes to the total light production.

A lamp depending on electro-luminescent gases is realized in its purest form in Arons-Cooper Hewitt's mercury vapor lamp. In this the total light emission proceeds from the current-carrying vapor column. The lamp consists, essentially, of a long, evacuated glass tube, containing at one end a mercury cathode and at the other, a metallic anode, which latter remains cold and non-luminous.

In contrast with the plain carbon arc, neither the cathode nor the anode of a mercury vapor lamp emits any part of the light. Moreover, the energy consumed at the cathode is fully accounted for by the work of vaporization and ionization.

Within the luminous gas column of a mercury lamp the potential gradient $\frac{dV}{dx}$, — at least between points sufficiently far from the electrodes * — is remarkably uniform and the electrical energy there consumed is converted almost completely into luminous radiation.

Küch and Retschinsky have conducted a series of experiments with "Quartz" lamps, the results of which are shown in Fig. 45.

We see from this that the specific efficiency (Hefner candles per watt) of the mercury vapor lamp is relatively great. The efficiency increases with the vapor pressure and with the watt consumption. The curve tends asymptotically towards a limiting value, about 5.6 *HK*/watts, at which value the quartz glass begins to soften.

In this connection it should be pointed out that the

* Cf. J. Pollak's beautiful determination of the potential within mercury arcs. Ann. d. Phys., 19, 217 (1906).

mechanism of light production in the mercury arc is such as to make this apparently favorable efficiency rather doubtful from a physiological point of view. The distribution of energy in the mercury spectrum, as illustrated (according to Coblentz and Geer), in Fig. 46, shows that the visible radiation is confined principally to two sharp lines,

Hg α; wave length $\lambda = 0.546\ \mu$,
Hg β; wave length $\lambda = 0.579\ \mu$.

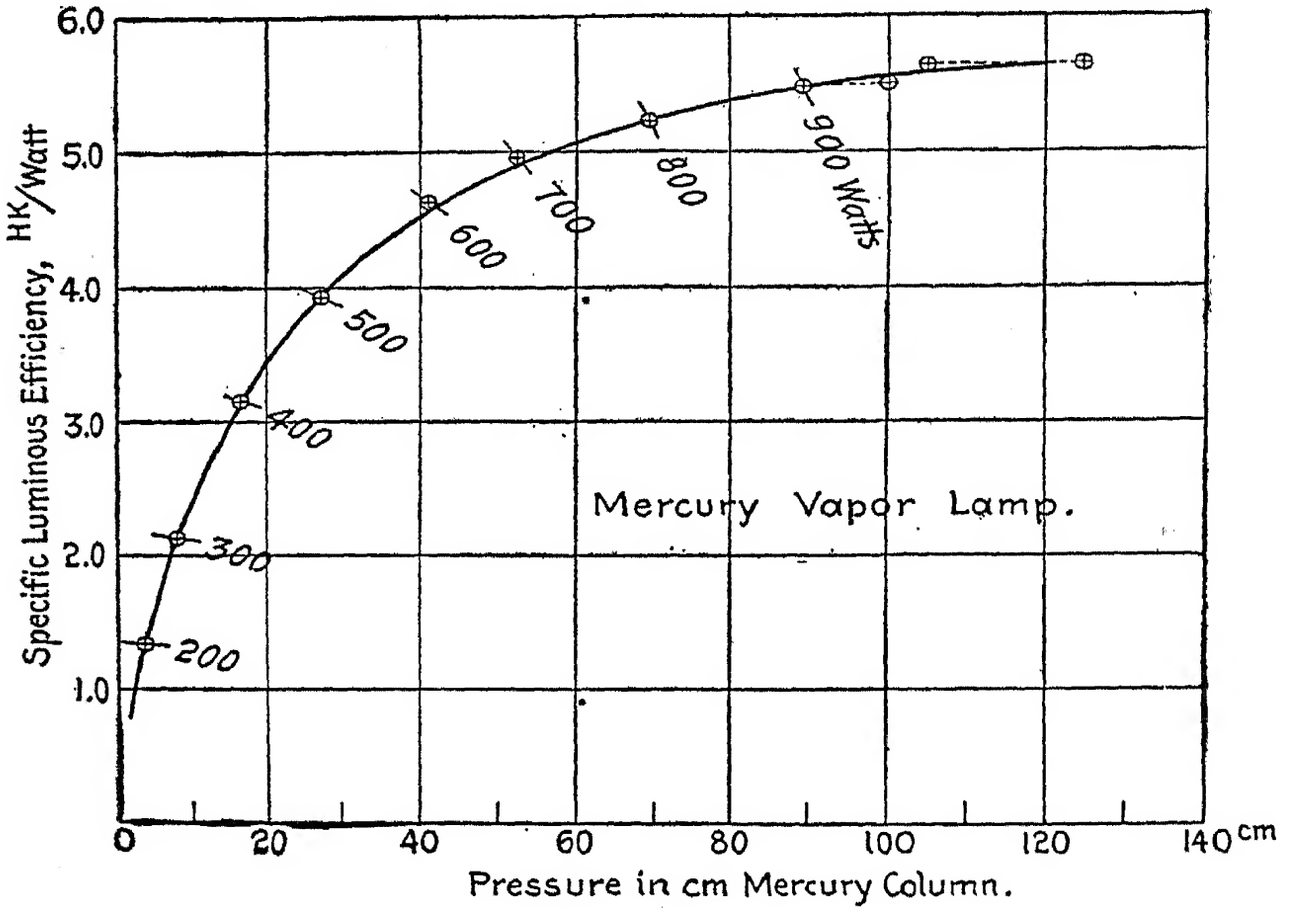

FIG. 45.

The light from the mercury arc accordingly is of a livid bluish-green color, entirely deficient in any of the warmer, richer hues.

Thus—both from a physiological and an esthetic point of view—the mercury arc can as yet hardly be accepted as a substitute for the harmonious sensation which we call light or, more precisely, natural white light, being

lacking in qualities we have a right to expect in a satisfactory source of illumination.

The physiological effect produced in the cerebral centers of vision * by the mercury arc have, however, only very little similarity to subjective light sensations.

We might illustrate this by an acoustic analogy. Let it be supposed that from the disk of a gramophone has

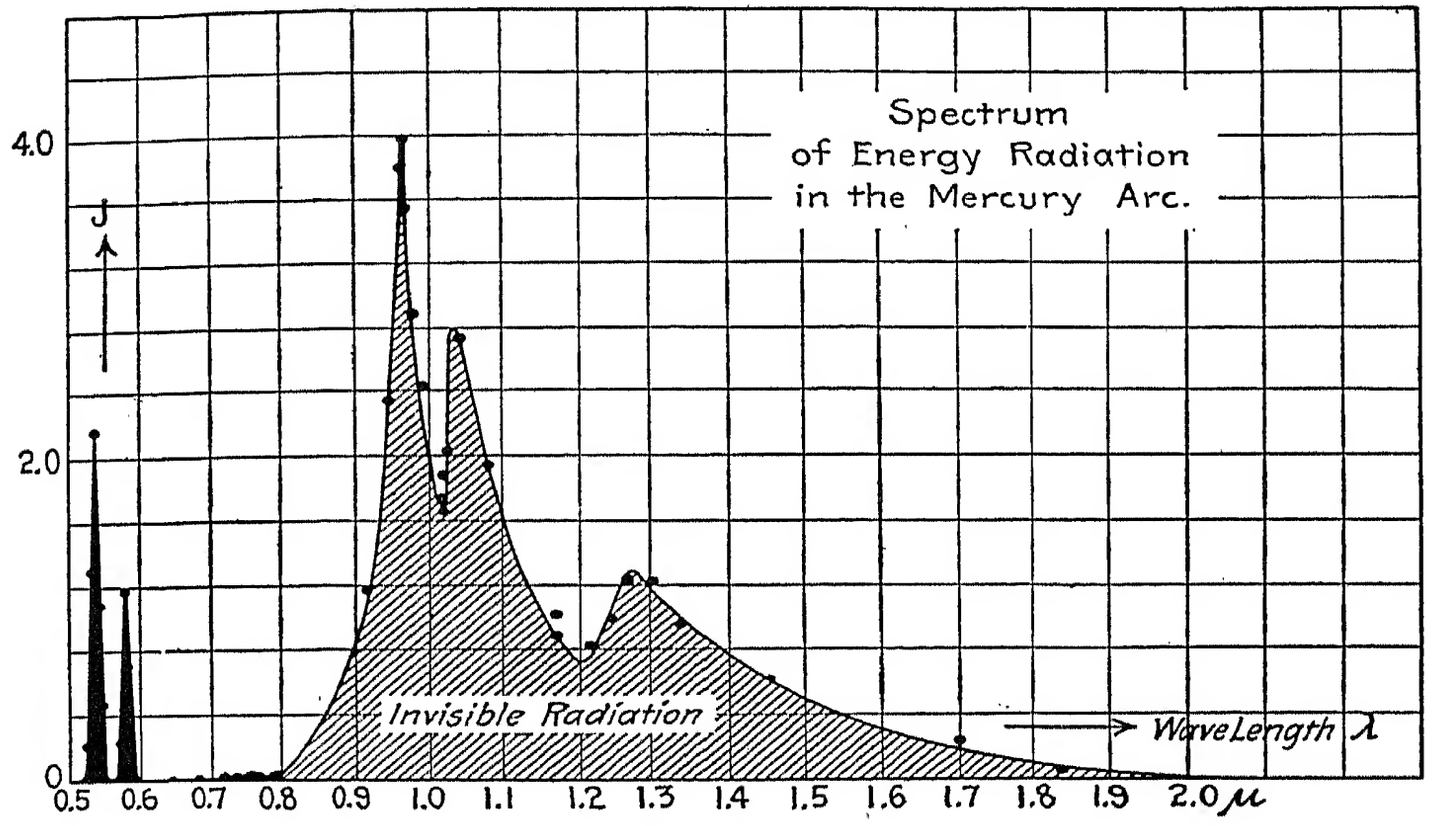

FIG. 46.

been cut away, irregularly, all harmony-producing portions, in order to economize with the power of the driving motor. We certainly would be justified to decline to recognize as *music* the physiological stimulations (heptachords, noise) produced by a machine so mutilated.

The anode of a mercury lamp, as made at present, consists of a metal disk the surface of which is made so large that the energy density there will always be kept

* The optic nerve itself is insensible to light (sensitive spot, *fova*). It seems exclusively to play the part of a transmitting organ.

low enough to prevent the anode from becoming unduly heated.

The electrical energy consumed at the anode, which, according to Pollak's determinations, can be estimated at 25 per cent, or more, of the total energy, may be considered as, to all intents and purposes, lost for the light production.

It does not seem entirely without prospects of good results to investigate whether, and to what extent, this portion of the energy could be usefully applied to light production and color correction. At present it goes to waste in the so-called condensing chamber of the lamp. To accomplish this object the energy density of the anode should be raised, in some suitable manner, to the point of incandescence.

At any rate, it appears very desirable to try out refractory conductors of the second class as anodes in vacuum lamps of this and similar kinds. Such substances have shown themselves to possess remarkable and important properties in regard to emission of electrons as well as to anodic radiation (atomic rays, anode rays). Their practical application to electric-light engineering is only a question of time.

It should be mentioned, in this connection that with a cold anode the mercury arc can exist only as long as the mercury surface remains a cathode, since it is by the vaporization of this surface that the free electrons are produced (electric valve action). Consequently, mercury vapor lamps can be operated only on direct current. If connected to an alternating-current source the arc will go out when the current reverses its direction, that is, the cold metal electrode will become the cathode (Cooper Hewitt's and Wehnelt's mercury interrupters).

As we have seen in the foregoing, the existence of an

arc or any other gas discharge is theoretically impossible unless the negative current base (the cathode surface) is in such a condition that it can emit electrons, i.e., units of mass carrying negative charges of electricity.

This condition, in the author's opinion, generally is satisfied when, at the cathode surface, vaporization in the broad sense of the word (disgregation) takes place and when this is combined with a certain amount of work of thermal disgregation.

In the case of solid bodies (metals) a relatively high temperature (temperature of incandescence) is usually required for this, it is true. But incandescence of the cathode, is not at all, *per se*, a necessary prerequisite condition for the formation possibility of an electric arc. For example, even comparatively cold liquids (aqueous solutions, fused metallic salts) are excellent cathodes and are capable of producing surprisingly beautiful arcs. It is necessary for this, of course, that the before-mentioned vaporization and dissociation phenomena take place at the negative current base.*

As a matter of fact, however, solid bodies do not, as a rule, show any marked ability to emit negative ions except at high temperatures. Furthermore, there is this essential difference between metals and solid conductors of the second class, that the emissivity of the latter is by far superior to that of the metals.

If, in a mercury vapor lamp, a glowing oxide electrode, which is itself a radiator, be substituted for the cold metallic anode the mercury arc can be maintained also with alternating current.

A practical more than a theoretically inherent drawback of vacuum lamps with solid electrodes of conductors

* Cf. Rasch, "Über Stickstoffverbrennung zwischen Leiter zweiter Klasse." Zeitschr. f. Elektrochem., p. 669 (1907).

of the second class is the fact that the electrode vapors are deposited on the walls of the glass and in the course of time more or less impair its transparency.

We shall have to depend on further experimental work to show whether and to what extent it is possible and of practical advantage to use for cathode or anode, as the case might be, in lieu of the boiling pool of mercury, solid, fused or aqueous solutions under suitable pressure.

According to the author's experience we have here a possible means for realizing monochromatic sources of light or sources with any desired selective radiation.

The question whether and under what circumstances such illuminants would be suitable to satisfy commercial requirements, obviously, cannot be discussed here.

CHAPTER VIII.

EFFICIENCY OF COMMERCIAL TYPES OF ARC.

§ 34. Practical Standard for Light Measurements.

It will suffice here to consider the efficiency of the more generally used kinds of arcs. By efficiency η is meant simply the light intensity in hefner candles per watt power consumption. ($\eta = HK/\text{watts.}$)

The reciprocal expression (watts/HK) is objectionable as a measure of efficiency,* since the specific consumption, watts per hefner candle, increases with the uselessness of a lamp, or, in other words, decreases hyperbolically the more economical a lamp is as an illuminant.

By spherical efficiency, $\eta_{\bigcirc}$, will be understood the mean spherical intensity divided by watts consumed. Similarly, the hemispherical efficiency, $\eta_{\cup}$, will be used to express the mean lower hemispherical intensity ($H_{\cup}$ in hefner candles) per watt. The mean value of the lower hemispherical candle power is obtained by measuring the total light flux below the horizontal and distributing it, by calculation or by graphical methods, uniformly over the lower hemisphere.†

* It has become more or less common practice to express the degree of economical operation of a lamp by its specific power consumption (watts/HK), which, especially to laymen, is turning matters upside down. This term tends to a confusion of the facts, and its use should be discouraged.

† The light distribution of arc lamps and the geometrical and optical laws which govern such distribution have been exhaustively treated in (J. Zeidler, "Die elektrischen Bogenlampen") and (Paul Högner, "Lichtstrahlung und Beleuchtung") of this collection of monographs. The reader, therefore, is referred to these two books for more complete information on this subject.

§ 35. Direct-Current Plain Carbon Arc.

In Table 27 and Fig. 47 will be found data, by Uppenborn, on the efficiency of the plain carbon arc as met with in actual practice.

TABLE 27. EFFICIENCY $\eta_{\smile}$ OF PLAIN CARBON ARC IN DIRECT-CURRENT LAMPS.

(UPPENBORN.)

Current J, amperes.	Lamp voltage e, volts.	Total energy S', watts.	Hemispherical candle power $H_{\smile}$, HK.	Efficiency $\eta_{\smile}$ in HK/watt,		Difference.
				as measured.	as calculated.	
3	41.0	123	139	1.13	1.11	−0.02
4	42.0	168	212	1.26	1.27	+0.01
5	43.0	215	308	1.43	1.41	−0.02
6	43.5	261	400	1.53	1.53	±0
7	44.0	308	505	1.64	1.64	±0
8	44.4	355	620	1.75	1.74	−0.01
9	44.8	403	740	1.84	1.83	−0.01
10	45.2	452	860	1.90	1.92	+0.02
11	45.5	500	990	1.98	2.00	+0.02
12	46.0	552	1125	2.04	2.03	−0.01

It will be noticed that there is a continuous increase of the hemispherical efficiency $\eta_{\smile}$ with increasing watt consumption eJ (that is, with increasing size of lamp). A close examination of Uppenborn's data shows that there obtains between them the relation

$$\frac{d\eta_{\smile}}{\eta_{\smile}} = \frac{1}{3}\frac{dS'}{S'},$$

where $S' = eJ$ (watts) denotes the total energy transformed in unit time, i.e., approximately the total energy radiation of the lamp.

By integration we obtain the equation:

$$\eta_{\smile} = A\sqrt[3]{S'} + B\ (HK/\text{watt}). \qquad (1)$$

The empirical constants A and B have, for carbon arcs up to 12 amperes, the values

$$A = 0.298,$$
$$B = -0.373.$$

As shown by Table 27 (column 7) values for $\eta_{\smile}$ calculated from this equation (1) agree closely with Uppenborn's results.

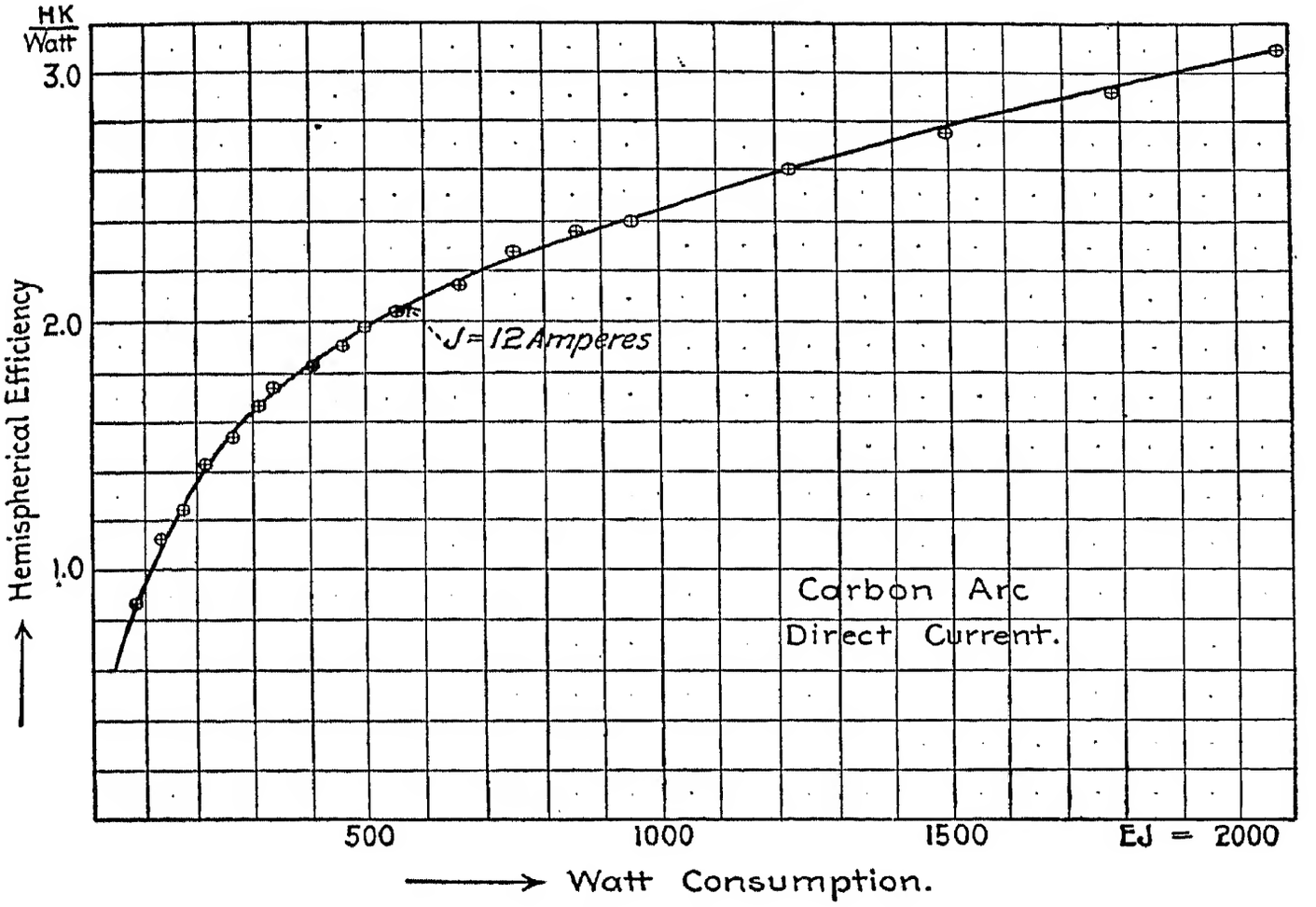

FIG. 47.

For currents over 12 amperes Uppenborn gives the figures contained in Table 28, on the following page. If these higher current values be inserted in equation (1) it will be found that also in this case the specific efficiency $\eta_{\smile}$ increases as the cube root of the total energy (S') transformed in the lamp.

TABLE 28. EFFICIENCY $\eta_{\smile}$ OF PLAIN CARBON ARC IN DIRECT-CURRENT LAMPS.

(UPPENBORN.)

Current J, amperes.	Lamp voltage e, volts.	Total energy S', watts.	Hemispherical candle power $H_{\smile}$, HK.	Efficiency $\eta_{\smile}$, HK/watt.	Remarks.
12	46.0	552	1125	2.04	$\eta_D = 0.2156\sqrt[3]{S'} + 0.30$
14	46.5	651	1390	2.14	
16	47.0	752	1710	2.27	
18	47.5	855	2000	2.34	
20	48.0	960	2300	2.40	
25	49.0	1225	3180	2.60	
30	50.0	1500	4140	2.75	
35	51.0	1785	5200	2.92	
40	52.0	2080	6400	3.08	

The constants A and B, however, at $J = 12$ amps. (approx.), abruptly change in value and become

$$A = 0.2156,$$
$$B = +0.30, \text{ thus, changing sign also.}$$

If we analyze the figures in Tables 27 and 28 it will become apparent that the two sets of data have been derived from test under different and not directly comparable conditions. The smooth curve in Fig. 47, on the other hand, gives no indication of such discrepancy.*

It is evident, then, that the efficiency ($\eta_{\smile}$) in the present example, has been appreciably affected by essential — and disadvantageous — changes in the operating conditions (for instance, in dimensions of carbons, length of arc, adjustment of the regulating mechanism,

* The object of the above remarks is, among other things, the purely didactic one of showing that the graphic method of representation — which is so much in vogue at present — at times is more apt to prevent than to promote a deeper insight into the mechanism of phenomena. At any rate, the graphic method usually is good enough only when one is satisfied with a superficial answer, giving an approximate idea of the course taken by a phenomenon. (Cf. the smooth curve, Fig. 47.)

etc.). Thus the constant B must be considered as arbitrary in character and without physical significance.

§ 36. Maximum and Hemispherical Light Intensity of Direct-current Carbon Arcs.*

The light issuing from the ordinary direct-current carbon arc is of maximum intensity at an angle of about 45 degrees with the horizontal. This characteristic is due to

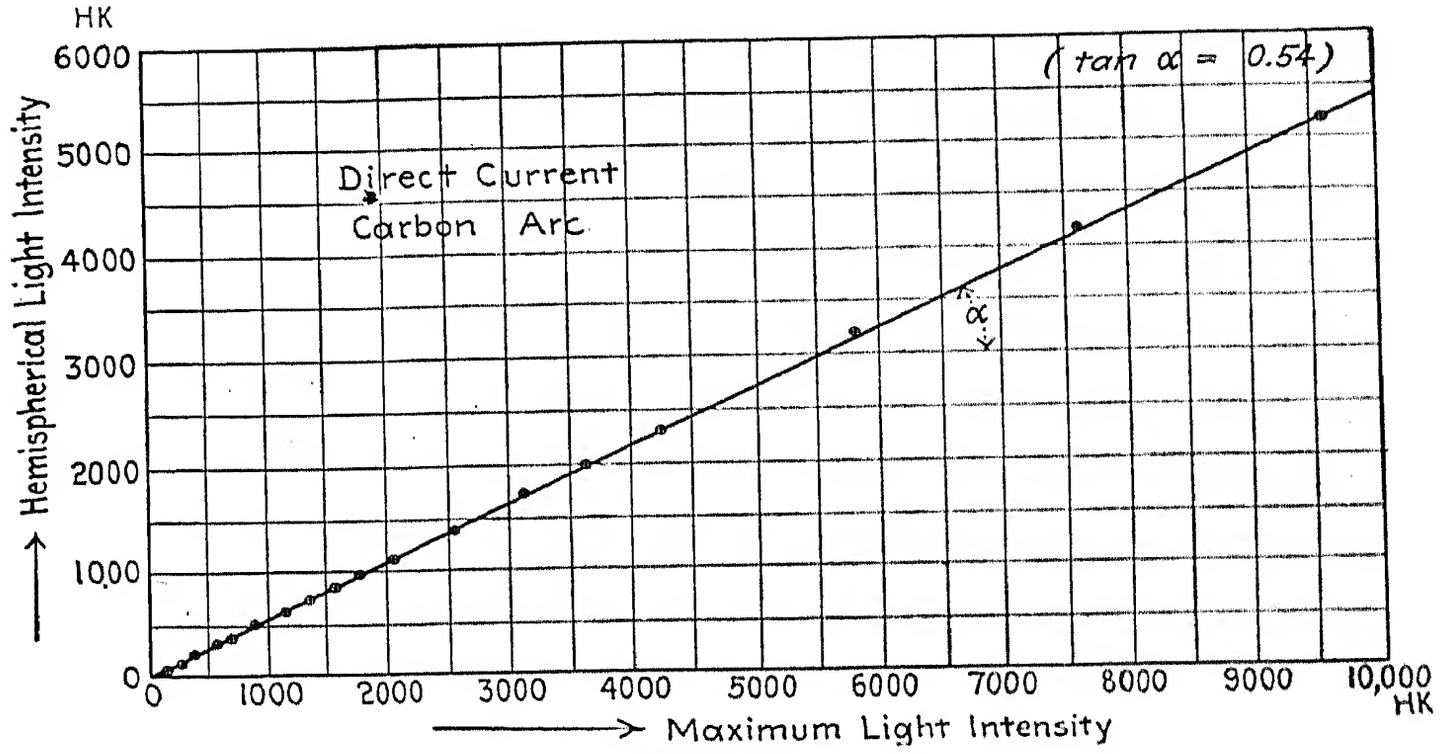

FIG. 48.

purely geometrical peculiarities such as the formation of an anode crater and the shadow cast by the cathode.

The light intensity curves are lemniscate-like figures having their origin at the arc hearth.

Fig. 48 shows, according to Uppenborn, the relation between the maximum and the mean hemispherical light intensity of direct-current arc lamps with plain carbon electrodes.

His results would seem to show that the relation be-

* Cf. also Volumes 6 and 8 of this series of electrotechnical monographs.

tween maximum intensity H_{max} and hemispherical intensity $H_{\smile}$ of the direct-current carbon arc can be expressed, for practical purposes,

$$H_{\smile} = 0.54\, H_{max}.$$

§ 37. Alternating-current Plain Carbon Arc.

The maximum intensity (H_{max}) of the alternating-current arc has been found by Uppenborn to be (Fig. 49)

$$H_{max} = 2.355\, S' - 788\ (HK).$$

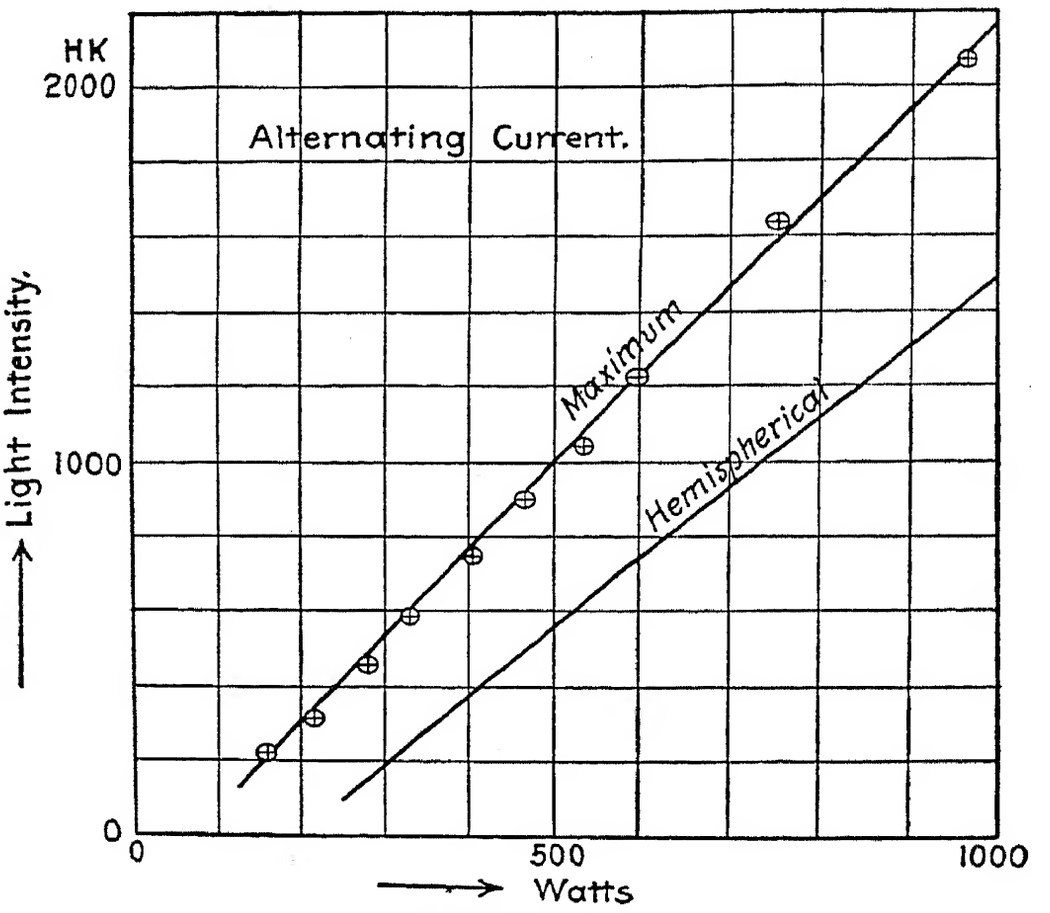

FIG. 49.

For the hemispherical light intensity ($H_{\smile}$) of alternating-current arcs (up to 25 amps., 700 watts) Wedding * gives the empirical linear relation

$$H_{\smile} = 1.4\, S' - 102\ (HK).$$

By using Wedding's formula we get, then, within its range of application, for the relation between hemi-

* E.T.Z., 1897, p. 716.

spherical and maximum light intensity of alternating-current plain carbon arcs, approximately

$$H_{\smile} = 0.6\ H_{\max.}$$

It seems hardly necessary to point out that the above numerical relations apply strictly only to the particular

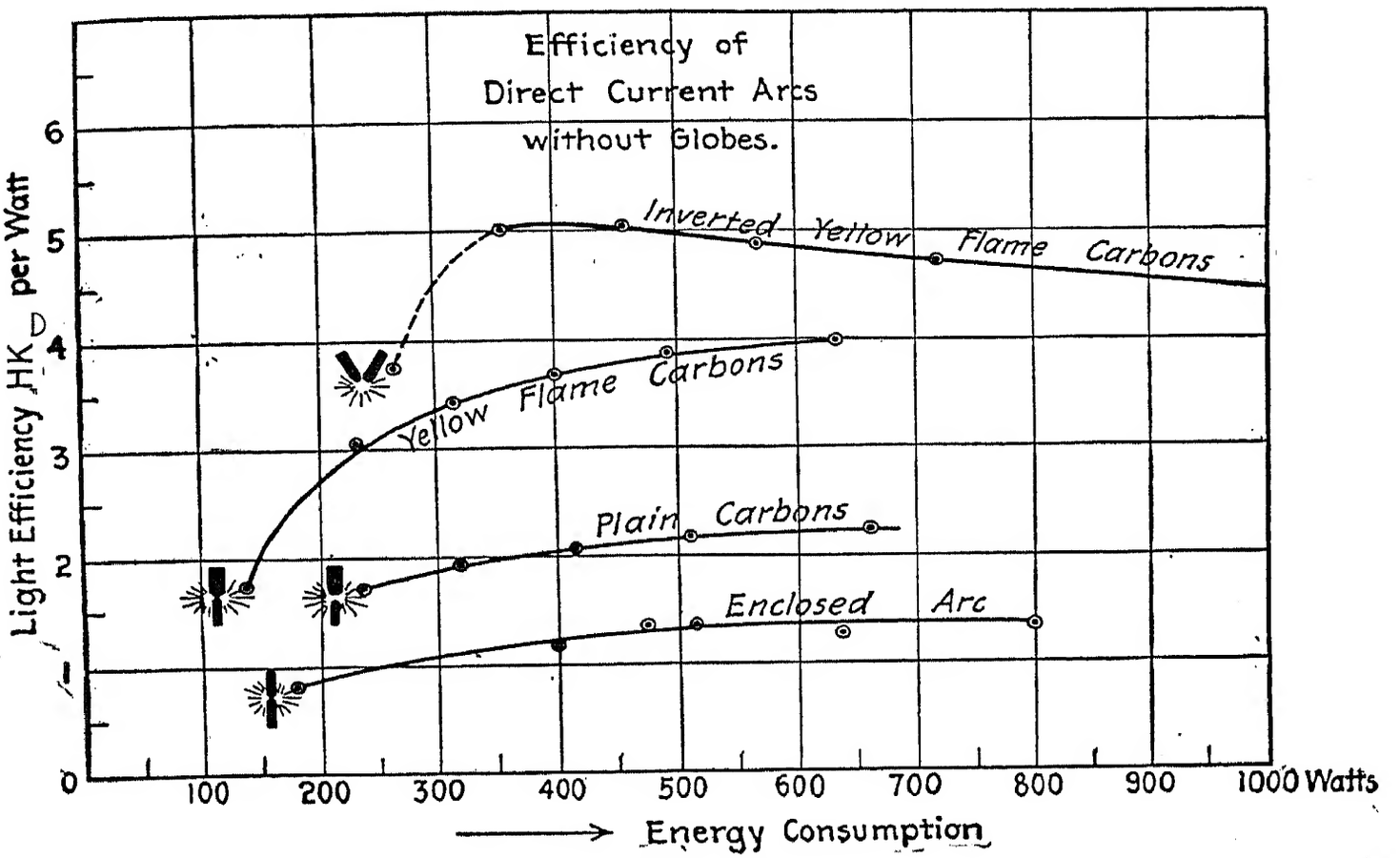

FIG. 50.

types of lamps and arrangements that were employed in the tests in question. Any material alteration of one or more of the individual factors (such as arc length, quality of carbon, arc voltage, etc.) obviously must result — as already intimated — in other numerical values of the coefficients.

The formulas here given, thus, are intended only to give a rough idea as to the order of magnitude of the relationship existing between the light intensity and the energy input.

For the purpose of easy comparison there have been given in Figs. 50 and 51, the results obtained by B. Monasch * in his tests of direct- and alternating-current lamps, without globes. These curves show, that with electrodes in vertical axial alignment and in enclosed arc lamps the luminous efficiency approaches, asymtotically,

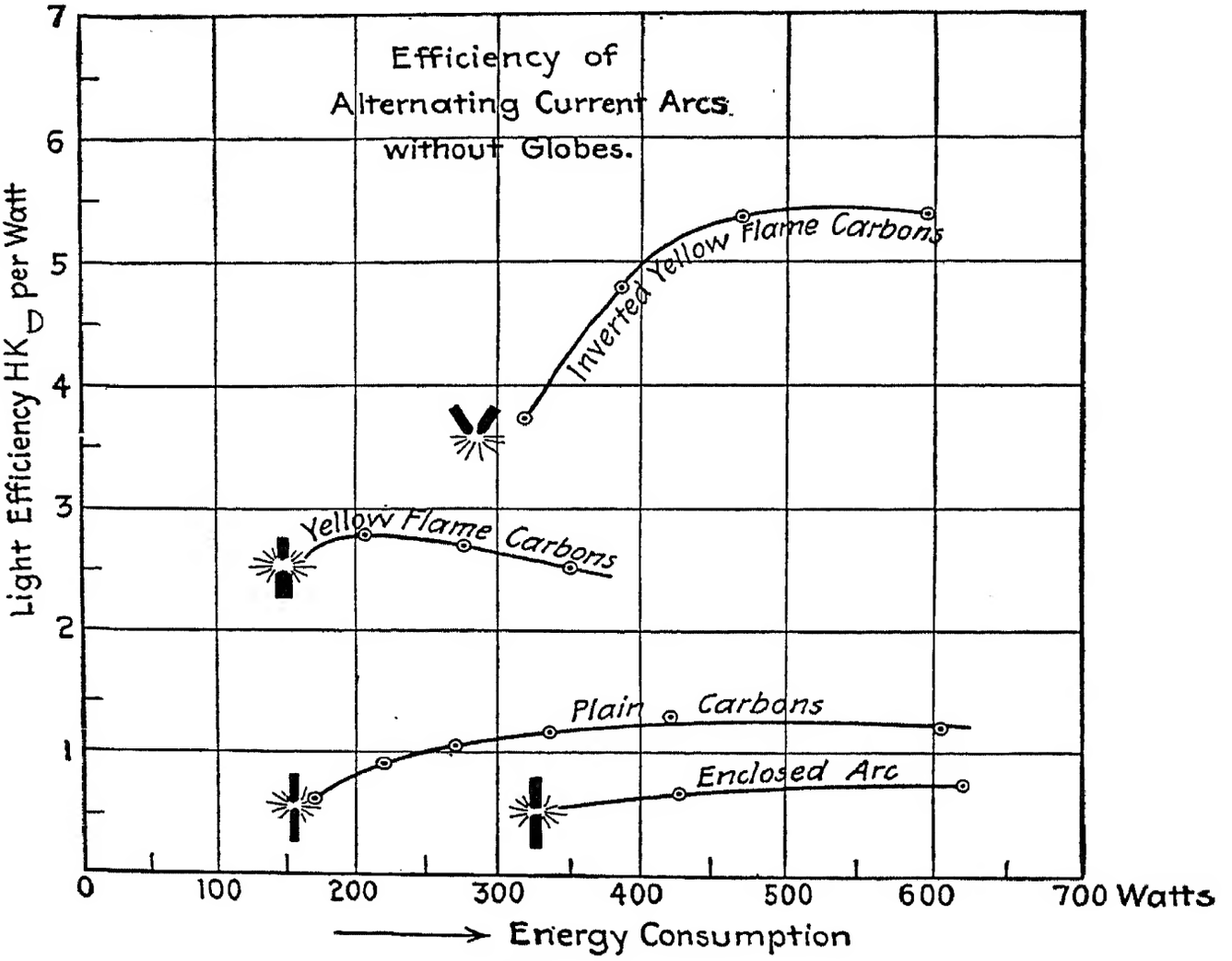

FIG. 51.

towards a maximum as the power consumption is increased. ($S' = eJ = \infty$.)

In the case of lamps with downwardly converging electrodes (see further below), the current threads (the flame) are artificially lengthened by the magnetic blow and it has been found that the efficiency reaches an

* Berthold Monasch, "Elektrische Beleuchtung," Hanover, 1906.

optimum value which corresponds to a definite watt consumption. From what we have explained before it is clear that this value depends, on the one hand, on the arc length and the determining factor thereof, the field strength of the blow magnet. On the other hand it is conditioned by what proportion of the light is emitted from the arc flame and what from the electrodes (temperature radiation), which proportion varies with the first-mentioned factors.

The Enclosed Arc.

The photometric efficiency of enclosed arc lamps in which the arc burns with restricted air supply (cf. § 6, pages 17 and following) is somewhat of the same order as that of modern incandescent lamps (cf. Figs. 50 and 51). The question of when it is economical to use enclosed arc lamps, naturally, depends on a number of commercial considerations.

In contrast with the other types of carbon arc, the enclosed arc is characterized by slow consumption, and consequently long life of the electrodes. Also, by a more efficient utilization of the supply voltage.

The pronounced occurrence of the photochemically active cyanogen bands makes the enclosed arc of especial value in connection with photochemical printing processes.

The Mercury Arc.

The mercury arc lamp consists, essentially, of a more or less evacuated glass tube (quartz glass), containing liquid mercury at one end and a solid electrode at the other. The mercury is connected to the negative side of the circuit and, thus, forms the cathode of the arc. The anode, a disk of iron or nickel, is connected to the positive side of the circuit.

By tilting the lamp body in some suitable manner (thus making a temporary short circuit between anode and cathode) or by some other form of starting the arc (preheating the cathode surface by means of spark discharges) mercury vapors are produced and form a luminous current path between the electrodes.

If — as has been done by Schott & Co., Jena — an ordinary carbon filament incandescent lamp be used as a series resistance, the efficiency, with normal current, will be 1.15–1.6 *HK* per watt. With mercury lamps run at high energy per unit length, as mentioned before, as much as 5.6 *HK* per watt is attainable (Küch and Retschinsky).

The principal appropriate use of the mercury arc lamp in its present form, — for physiological reasons to be explained later — would seem to be in connection with photochemical reproduction processes (photography, blueprinting, etc.)

§ 38. Colored Flame Arcs Between Electrodes Containing Materials which are Conductors of the Second Class.

The admixture of metallic compounds (fluorides, oxides, silicides, etc.) to arc lamp carbons results in a characteristic coloring of the arc flame and an extraordinary improvement of the efficiency, which may be tripled or quadrupled thereby.

The great conductivity of the vapors from conductors of the second class, besides, has made it possible to run arcs of great length (15 mm. or more) which emit as much as 25 per cent of the total light.

The increase of efficiency with increase of the percentage (p) of conductors of the second class (fluorspar) is shown by Table 29. This contains the results obtained by Wedding * with 9-ampere 45-volt direct-current arcs

* E.T.Z., 23, 704 (1902).

between downwardly converging carbons. As in Siemens' inverted regenerative gas burner and the modern Welsbach burners, the arc is inverted, i.e., forced downward through the blowing effect of a magnet.* (The Bremer type of lamp.)

TABLE 29. INCREASE OF LIGHT EFFICIENCY $\eta_{\smile}$ WITH PROPORTION (p) OF CONDUCTORS OF THE SECOND CLASS.

Positive carbon=8 mm.; negative carbon=7 mm.

Percentage calcium-fluoride, 100 p, per cent.	Mean hemispherical candle power, $H_{\smile}$.	Hemispherical efficiency, $\eta_{\smile}$ HK per watt.	$\frac{\eta_{\smile}}{\sqrt[3]{p+p_0}}$.	Remarks.
(0)	1173	2.185	12.0	$p_0=0.006$ is a constant representing amount of metallic impurities in the usual commercial grades of plain carbons.
8	1728	4.32	9.8	
15	2505	6.17	11.5	
20	2808	6.95	11.8	
25	3268	8.07	12.7	
30	3321	8.20	12.2	
35	3385	8.34	11.8	
40	3574	8.85	12.0	

Mean: $\mathcal{K}=11.7$.

As shown by Fig. 52 and Table 29, there is a steady increase of efficiency ($\eta_{\smile}$) with increasing percentage (p) of conductors of the second class. More especially, it appears that the efficiency increases as the "linear" rate of concentration of such substances in the arc flame, i.e., with the cube root of the proportion by weight (p).

The conclusion usually drawn from Wedding's investigation, namely that the efficiency cannot economically be improved after a certain maximum content has been reached accordingly is not correct.

From a graphical analysis of Wedding's data, Fig. 52, it follows that the hemispherical efficiency is given by

$$\eta_{\smile} = \mathcal{K}\sqrt[3]{p_0 + p}\ HK/\text{watt} \qquad (1)$$

* Jamin, Compt. rend., 88, 541 (1879).

and the spherical efficiency by

$$\eta_{\bigcirc} = \frac{\mathcal{K}}{2}\sqrt[3]{p_0 + p}\ HK/\text{watt}. \qquad (2)$$

According to Fig. 52 and Table 29:

$$\mathcal{K} = 11.7 \text{ and } p_0 = 0.006.$$

These equations give for the plain carbon arc ($p = 0$) a hemispherical efficiency of 2.12 HK per watt or a spherical efficiency of 1.06 HK per watt, which agrees with Monasch's values (Fig. 50).

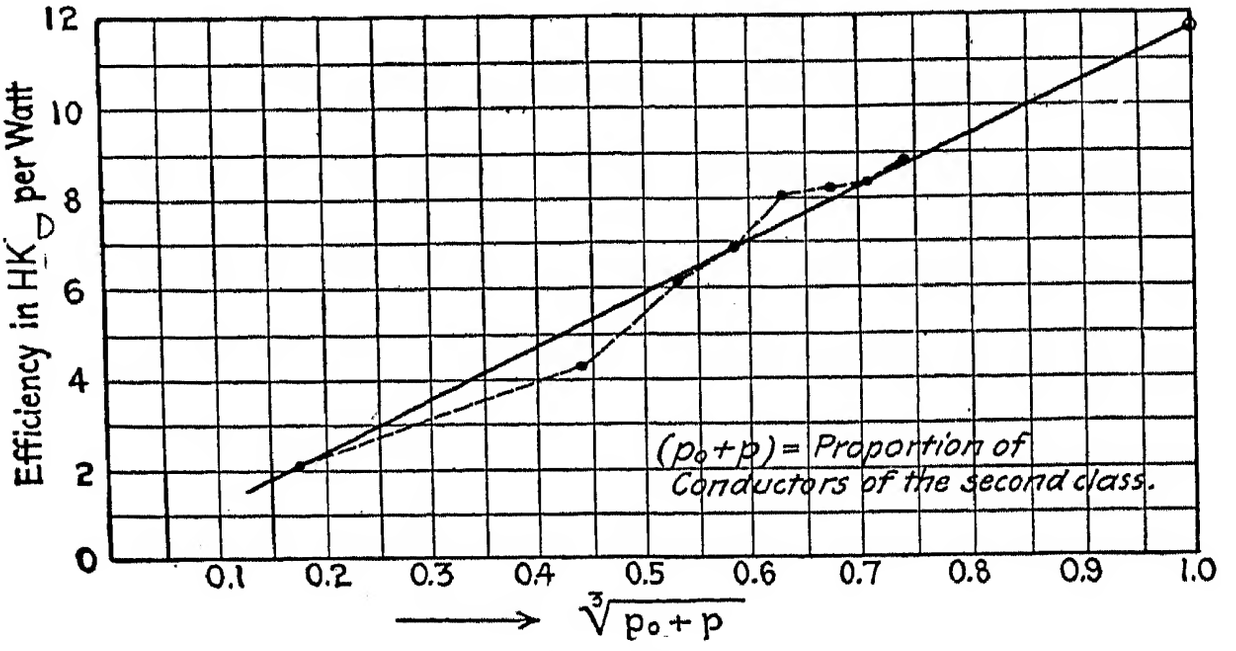

FIG. 52.

The pure electrolyte-arc ($p = 1$) would give, in accordance with this formula, an efficiency which is about five times as great as that of the plain carbon arc, or a hemispherical efficiency of 11.7 HK per watt. This corresponds to a spherical efficiency

$$\eta_{\bigcirc} = \frac{11.7}{2}\sqrt{1} = 5.8\,HK \text{ per watt},$$

or, in any event,

$$\eta_{\bigcirc} > 5.2\,HK \text{ per watt},$$

a value which the author has found experimentally.*

* See in this connection German Patents Nos. 117,214 and 137,788, March 18, 1899; also, E.T.Z., 22, 155, 256, 293, 374 (1901).

This result did not agree with the then accepted data as to the maximum light efficiency attainable. The latter, at the time (1899), was expressed by Tumlirz's so-called mechanical equivalent of light, then in general use, which stipulated 5.21 *HK* per watt only as the highest spherical efficiency obtainable with any source light.*

We know today of quite a number of lamps in which this degree of efficiency has been realized. It is not necessary or desirable to devote space here to an account of the controversy on this mooted question, which is, at present, devoid of any practical interest.

* H. Müller's statement [E.T.Z., **22**, 293 (1901)] that a source of light giving more than 5.2 *HK* per watt (such as the author has actually produced) must not show any heat effects, is an error plainly due to a pedantic distinction between heat rays, light rays and chemical rays. Its acceptance would lead to the absurd conclusion that bolometers, thermocouples and similar instruments for measuring the heat energy in the visible spectrum should not by rights give any indication at all. Müller's objection, moreover, has been completely refuted by later corrections and modifications in the data and views pertaining to the "mechanical heat equivalent of light."

Nernst, in commenting (1901) on the author's prior (1899) published work, states that at the accidental burning out of one of his glowers an arc was formed, but that the rate of consumption of electrodes of this kind would be too great to allow their practical application. According to the author's experience this was not the case. He has produced electrolyte-arcs which were maintained for from 15 to 20 minutes without requiring any feeding of the electrodes. Nernst points out that, singularly enough, and entirely contrary to what is the case in carbon arcs, the rate of consumption was greater at the cathode (due to disintegration, since obviously one cannot very well speak of "burning away" in connection with incombustible oxides) than at the positive electrode, and adds that this apparent anomaly "might have an important bearing on the theory of the arc." This statement requires correction, inasmuch as it has found its way into scientific technical works (Monasch, "Der elektrische Lichtbogen," p. 49). Nernst's statement is not in accord with actual facts. Rather, the reverse is true: the rate of consumption of oxide arcs is, in likeness with the carbon arc, considerably greater at the anode than at the cathode. See prior notes by the author referring to the oxide arc: Rasch, Zeitschr. für Elektrochemie, p. 669 (1907).

This much might be said, however, that the later investigations by Ångström of the so-called "mechanical heat-equivalent of light" have furnished data which fully explain the facts noted by the author in regard to oxide arcs and by Küch and Retschinsky in regard to mercury arcs.

As the author has pointed out in another place,* the previously accepted "mechanical equivalent of light" is meaningless, since physiological effects can no more be expressed in mechanical horse powers than can, for instance, Beethoven's "Ninth Symphony."

§ 39. Radiation Collectors. Notes on Further Possible Applications of Electric Flames.

Certain observations make it probable that flames as vehicles for electrical charges — i.e., flame arcs in the broadest sense of the word — are destined to play an important part in the quest after new sources of energy.

It therefore seems appropriate to devote a few final words to the mechanism of electrical conductivity (κ)†,

* E.T.Z., 22, 374 (1901).

† We have:

Conductivity $\kappa = \frac{1}{\rho}$; ρ is the electrical resistance of one centimeter cube at the absolute temperature $T = t + 273$.

$$\textit{Equivalent concentration } \eta = \frac{M}{\mathfrak{E}} = \frac{\text{Mass dissolved in gms. per cu. cm.}}{\text{Equivalent weight } \mathfrak{E} \text{ of solute}}.$$

$$\textit{Equivalent weight } \mathfrak{E} = \frac{A}{n} = \frac{\text{Atomic weight } (A)}{\text{Valency } (n)}.$$

Further, the ionic mobility λ_1 of the cation and λ_2 of the anion is defined by the additive expression $\lambda_1 + \lambda_2 = \frac{\kappa}{\eta}$.

If the ionic mobility (λ) be divided by the constant in Faraday's law ($\mathfrak{F}$ = 96,850 coulombs) we get $u = \frac{\lambda}{\mathfrak{F}}$, a velocity, i.e., the distance (cm.) which a dissociated mass-unit travels in unit of time (second).

electrolytic dissociation and velocity of reaction at high temperatures (T) such as exist in flame arcs, the more so as conditions in these are essentially different from those obtaining in aqueous solutions and at the low temperatures with which physical chemistry chiefly concerns itself.

True gases and, likewise, chemically pure fuels (such as pure carbon, hydrocarbons, etc.) can be considered as nearly perfect nonconductors (dielectrics) at ordinary temperatures ($\Theta = 291°$). Another characteristic of such substances is that they are very inert chemically, at low temperatures. However, their conductivity (κ) increases enormously with rise in temperatures. This increase is the more rapid the lower their conductivity (κ_1) and all the slower the greater the conductivity at the temperature $\Theta = 291°$. Finally, the conductivity of metals, which at temperature $\Theta = 291°$ is of a much greater order than that of dielectrics, decreases with increasing temperature, the reverse of what takes place in the case of dielectrics.

While for small temperature intervals in the neighborhood of the usual observation temperature Θ the conductivity at a temperature $T = \Theta + \vartheta$ may be expressed by the empirical equation

$$\kappa = \kappa_\Theta (1 + \alpha\vartheta) = \kappa_\Theta [1 + \alpha (T - \Theta)] \qquad (1)$$

this fails completely to hold if one should want to draw conclusions from observations made at the usual temperature $\Theta = 273 + 18 = 291°$, as to conductivity at much higher or lower temperatures.

As Rasch * and Hinrichsen † have shown, the rate of

* E. Rasch, Zeitschr. f. Elektrotechnik u. Maschinenbau., Potsdam, 1903, p. 18.

† E. Rasch and W. Hinrichsen, Zeitschr. f. Elektrotechnik, 1908, p. 41, and following.

change in conductivity (κ) can be expressed by the differential equation

$$\frac{d\kappa}{\kappa} = \nu \frac{dT}{T^2}, \tag{2}$$

which, by integration, gives

$$\kappa = \mathfrak{K} e^{-\frac{\nu}{T}}. \tag{3}$$

That is, the dielectric conductivity (κ) increases rapidly with rise in temperature (T), not to infinity, however, but asymptotically towards a definite maximum value $\mathfrak{K}$ which would be reached at $T = \infty$.*

Analogously, we may write

$$\lambda = \mathfrak{L} e^{-\frac{\nu}{T}}, \tag{4}$$

where λ is the ionic mobility as defined (see above) in physical chemistry, and ν a material constant having the same value as in equations (2) and (3)†.

Using the values in the tables, usually represented by the empirical equation (1) ($\Theta = 273 + 18 = 291°$) one finds

$$\frac{d\kappa}{\kappa}\frac{1}{dT} = \alpha \text{ (according to equation (1))},$$

$$\frac{d\kappa}{\kappa}\frac{1}{dT} = \frac{\nu}{T^2} \text{ (according to equation (2))},$$

from which it follows that

$$\alpha = \frac{\nu}{T^2}.$$

The temperature coefficient α consequently is very great for low temperatures but decreases in value with increasing temperature. If, further, α_Θ is the temper-

* The validity of this law has recently been tested up to very high temperatures ($T = 1958°$) by the beautiful experiments of M. v. Pirani and Werner v. Siemens. [Zeitschr. f. Elektrochem. 15, 973 (1909).]

† For all monovalent ions in aqueous solutions the constant $ln\mathfrak{L}$ is = 10.47 (approx.).

ature coefficient determined at a temperature $T = \Theta$ as generally found in physical tables for $\Theta = 291°$, we can find the numerical value of the exponential material constant from the formula *

$$\nu = \alpha_\Theta \Theta^2 = \alpha_\Theta \, 84{,}681. \qquad (5)$$

The constant ν expresses the rate of increment of conductivity (κ), ionic mobility (λ),† velocity of reaction and degree of dissociation, with increasing temperature of the system.

The author's experiments on zirconia-yttria electrodes, which have been carried out up to a temperature $T = 1260°$, have given $\nu = 11{,}200$.

With sufficient degree of approximation for practical purposes — as long as the absolute value of $\kappa = \frac{1}{\rho}$ is small — one can write, also,

$$T ln \frac{1}{\kappa} = T ln \rho = \text{const.} = \nu. \qquad (6)$$

In accordance with the above the conductivity of, for example, a zirconia-yttria electrode at room temperature ($\Theta = 291°$) doubles in value for a temperature increase of 7.5° C.

* The numerical value of ν is entirely independent of the units in which conductivity (κ), ionic mobility (λ), equivalent concentration (η), etc., are measured and expressed, as long as the absolute temperature T is expressed, always in centigrade degrees. This fact, naturally, gives more universal applicability to equations (2) and following, since thereby the obscuring influence of arbitrarily chosen units of measurement is eliminated. In a physical sense ν is a definite, characteristic temperature.

† As Rasch and Hinrichsen (l. c.) have shown, there exists a remarkable relation which applies to all ions in aqueous solutions at $\Theta = 291°$, namely,

$$\alpha_\Theta \, \text{Log} \, \lambda_\Theta = A = \text{constant.}$$

The numerical value of this universal constant A is, for monovalent ions, 0.03902 and for divalent ions, 0.0419, or a mean value $A = 0.0405$ (approx.).

In the electrostatic system conductivity is a velo and resistivity the reciprocal value of a velocity. T for the mechanism of conduction in dielectrics

$$\frac{du}{u} = \frac{d\kappa}{\kappa} = \frac{\nu dT}{T^2}$$

and, after integration,

$$u = Ue^{-\frac{\nu}{\vartheta}} \ldots \text{ cm./sec.}$$

But in our physical conception of the Universe considered impossible for a mass of any kind to n with a velocity greater than that of light ($c = 3$ cm./sec.).*

It is necessary, therefore, to assume for electro maximum velocity $u_{max} = U = c = 3.10^{10}$ cm./sec. reasons which we have not space here to discuss, equation (8), denotes the temperature of the moving unit (the electron), which temperature is not necess identical with the mean temperature T of the body which the elemental radiation centers, the electrons, projected.

If i = amps./cm.^{2} denotes the current density o oxide electrode at a temperature T, our equation g us†

$$\frac{di}{i} = n\frac{dT}{T^2},$$

$$i = \mathcal{J}e^{-\frac{n}{T}}.$$

* The postulate, that everything which takes place must necessar represented by concrete or physical transformations in a three-dimen space, does not seem sufficiently warranted. The modern electrodyn of Minkowski finds it necessary to imagine a four-dimensional Uni the need of which had been felt already by Weber and Zöllner som ades earlier.

† An equation of the same form has been arrived at by the a

If with N we denote the number of negatively charged electrons emitted from a unit of surface (1 cm.^{2}) in the unit of time, each electron carrying a charge $\epsilon = 4.69 \times 10^{10}$ (electrostatic units), i.e., the so-called fundamental charge of electricity, then

$$i = \epsilon N,$$

$$\epsilon N = \mathcal{J} e^{-\frac{n}{T}}. \tag{11}$$

$\mathcal{J}/\epsilon = \mathfrak{N}$ is the maximum electronic density and consequently

$$N = \mathfrak{N} e^{-\frac{n}{T}}. \tag{12}$$

From experiments made by W. Westphal, Deininger and Jentzsch with incandescent oxide electrodes in vacuo it appears that the constant n in the foregoing equations * is approximately the same for the oxides of Ca, Sr, Ba, Y, Zr, Ce, La and Th, namely, $n = 38{,}500$. The cathode drop of potential was then about 3.3 volts.

The constant $\mathfrak{N}$, that is, the maximum concentration of electrons, may be estimated as being of the order $\mathfrak{N} = 5.10^{22}$.

The relations briefly touched upon in the preceding

"Fortschrittliche Prinzipien," p. 16 (1903), for the rate of increase of surface brightness, Ψ with temperature T,

$$\Psi = \Psi_m e^{-\frac{K}{T}} (HK/mm^2).$$

The constant K has the same value for polished surfaces and black bodies, namely $K = 25{,}850$. Maximum surface brightness Ψ_m is in round numbers 233,000 HK/mm^2.

* O. W. Richardson [Phil. Trans., 201, 516 (1903)] has deduced the equation $N = n\sqrt{\frac{RT}{2\pi m}}\, e^{-\frac{\Phi}{RT}}$, which contains four empirical coefficients.

Similarly, A. Königsberger has suggested an exponential formula with four empirical coefficients, to describe the dependence of electronic condition of temperature.

Neither theory nor experimental facts seem to furnish adequate reasons for either of these two formulas.

paragraphs show that we possess, in the cathode of the electric arc, a very simple device for the production of electrons in definite and large numbers. Furthermore, since the electrons are ultra-atomic, smallest possible mass units, out of which the chemical atoms are formed, the electric arc provides a means for the splitting up of matter, which perhaps makes the synthesis or transmutation of chemical elements not entirely beyond possibility in the future.

These views and those expressed in an earlier portion of this book (page 163), namely that the emission of electrons is, in the last analysis, a disgregation phenomenon — an evaporation process in the widest sense of the word — seem to be substantiated by the peculiar fact that Wehnelt's modification * of the author's oxide electrodes will, in the course of time, suffer "fatigue," i.e., will lose their ability to emit electrons. This was not the case with the author's electrodes, which, being in the form of solid rods, possessed greater active mass.

If, further, we emancipate ourselves from the notion created by the ordinary electric arc, that the existence of a cathode necessarily implies the coexistence of an anode immediately opposite; or, in other words, if we consider unipolar discharges (such as brush and point discharges from electrostatic machines) it becomes evident, in view of the foregoing, that glowing cathodes and indeed all glowing bodies, flames, etc., constitute radiators which permit relatively great current densities and thus make it possible to send forth large quantities of electricity (streams of electrons) into space (radiotelegraphy).

Conversely, an electrode surrounded by free electric charges constitutes — provided it has a high temperature

* A thin spot of oxide material — and thus of very small total mass — on a sheet platinum cathode in a vacuum tube. Cf. p. 141.

— a collector of great radius of action R, that is, with an effective capacity ever so many times greater than the electrostatic capacity (R_0) corresponding to its geometrical dimensions.

The utilization of the energy of the earth's field — an idea entertained by H. Hertz among others — does not seem impossible by means of the radiation collectors discussed above. Stefan-Boltzmann's law of radiation lends support to such a proposition. According to this law, the energy radiated into space (of temperature T_0) by 1 sq. cm. of incandescent surface (of temperature T) in unit of time can be expressed by

$$\mathfrak{S} = \sigma\,(T^4 - T_0^4) \text{ watts/sq. cm.}, \qquad (13)$$

wherein the constant σ, according to the latest investigations,* has the value $\sigma = 6.30 \times 10^{-12}$ watts/cm.†

If a constant potential difference ΔV exist between an incandescent body and the surrounding space, the former, at 3725° C., for example, would radiate, according to equation (13), energy at the rate of 1.6 kilowatt per sq. cm.‡ This is a reversible process independent of algebraic sign, i.e., of the direction of flux.

The potential gradient $\frac{\partial V}{\partial H}$ of the earth's field, accord-

* By Féry; Ann. d. chim. et d. phys., 17, 267 (1909).

† The old value ($\sigma = 5.32 \times 10^{-12}$), determined by Kurlbaum, thus is considerably lower. It so happens — which is quite a convenient fact to know in illuminating engineering — that a light-emitting surface at an absolute temperature $T = 2000°$ C. radiates 1 watt per sq. mm. or approximately 1 *HK* per sq. mm. The term T_0^4 may be omitted and the equation written

$$\mathfrak{S} = \left(\frac{T}{2000}\right)^4 \text{watts/sq. mm.}$$

‡ As we have learnt in the foregoing (p. 155), carbon electrodes at arc temperatures will endure a current density of 0.688 amp. per sq. mm. at the active spots of the tips.

ing to meteorological measurements, amounts to about 275 volts per meter difference in altitude (∂H). Two radiation collectors — flames for instance — 360 meters (H) vertically apart and connected by an insulated cable, consequently would have a potential difference of 100,000 volts. This voltage would be sufficient, in the form of a low-current discharge, to give sparks 15 cm. in length, or would, as a high-current brush discharge, produce one of enormous magnitude.

If we conceive of the earth as a condenser in the sense of electrostatics, and as insulated in the cosmic space, we find, from the geometrical capacity of the earth, according to Chwolson:

Its negative charge 1.3×20^6 coulombs (amps./secs.).
Its negative potential $V = 10 \times 10^8$ volts.

This gives us for EJt approximately 24.7×10^{24} watts/secs. If one should produce a terrestrial short circuit, by means of a grounded radiation collector — such as an arc flame — such a short circuit would represent an electrical work of about $79{,}500 \times 10^{10}$ kilowatt-years.

There is hardly reason to fear, however, that the electrical energy of the earth's field would thereby be exhausted. As a matter of fact there is little room for doubting that, by virtue of its radiation activity, the earth is electromagnetically linked to the sun (and more or less directly also to other radiating celestial bodies). This view seems to be abundantly borne out by the disturbances suffered by the earth's magnetic field coincident with solar disturbances (sun spots).*

* A radiation collector thus abstracts a certain quantity of energy from the earth (T = 300° C. approx.), and this energy, in doing motive work, drops to a lower temperature, viz., that of the cold interstellar space (T = 0). It is self-evident that the first and the second principles of thermodynamics are not violated hereby. If one were to abstract from the earth

A discussion of the question whether the quantities of energy thus convertible per unit of time would be of economic importance is not here in place. This would depend on the energy density in the atmosphere and on ionization radius, or radius of action R of the radiation collectors. Only actual experiments can throw light on this question.

It may be mentioned, however, that if a radiation collector at rest has a radius of action R (effective capacity of the flame) this radius will be increased u times, if u is the velocity of the radiation collector with which it moves horizontally—something like an airship—sweeping over the surface layers of the earth's electric field.

This much is certain: such electrical flames would offer a perfect protection against atmospheric discharges (lightning). Probably, in the future, they could find application as sensitive detectors in radiotelegraphy. But these radiation collectors deserve attention also in other respects, being pregnant with possibilities for further applications of the so-called electric arc.

by means of electrical devices of the kind indicated a considerable amount of energy (heat) for motive purposes, this would have as a final result a temporarily accelerated rate of decrease of the earth's temperature (T = 300°C. in round figures). This might be a cause for alarm if the earth were perfectly isolated cosmically. Such is far from being the case, however. It has been estimated — on the basis of Féry's (l.c. page 185) recently corrected solar constant — that the total radiation received from the sun by the illuminated half of the earth corresponds to a rate of energy something like $18{,}500 \times 10^{10}$ kilowatts per second. Furthermore, a lowering of the earth's temperature (T_E) without simultaneous lowering of the solar temperature (T_S) would contradict Stefan-Boltzmann's law, $\mathfrak{S} = \sigma (T_S^4 - T_E^4)$. If the earth's temperature (T_E) should fall, the total radiation $\mathfrak{S}$ absorbed by the earth would increase simultaneously.

Thus the secular rate of cooling of the earth seems to be dependent on that of the sun and of other radiating celestial bodies cosmically linked to it.

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